MAIN CHANNEL PROCESSES

Flow in a watershed is classified as overland or channelized. The primary difference between the two flow processes is that water storage and its influence on flow rates is considered in channelized flow. Main channel processes modeled by SWAT include the movement of water, sediment and other constituents (e.g. nutrients, pesticides) in the stream network, in-stream nutrient cycling, and in-stream pesticide transformations. Optional processes include the change in channel dimensions with time due to downcutting and widening.

CHAPTER **23**

EQUATIONS: WATER ROUTING

Open channel flow is defined as channel flow with a free surface, such as flow in a river or partially full pipe. SWAT uses Manning's equation to define the rate and velocity of flow. Water is routed through the channel network using the variable storage routing method or the Muskingum river routing method. Both the variable storage and Muskingum routing methods are variations of the kinematic wave model. A detailed discussion of the kinematic wave flood routing model can be found in Chow et al. (1988).

23.1 CHANNEL CHARACTERISTICS

SWAT assumes the main channels, or reaches, have a trapezoidal shape (Figure 23-1).
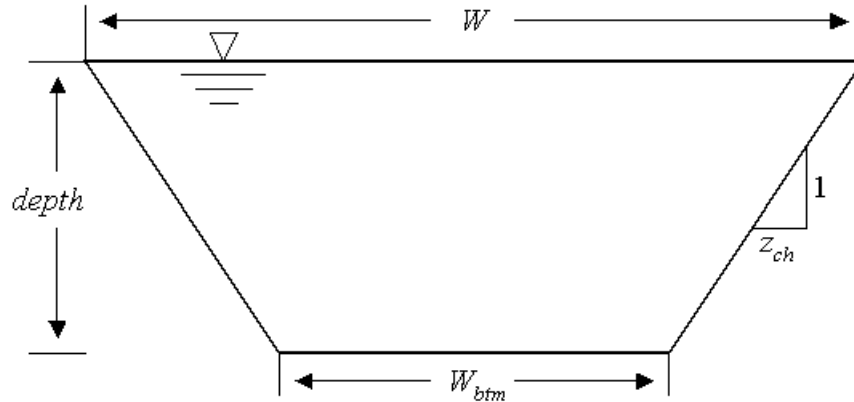

Figure 23-1: Trapezoidal channel dimensions

Users are required to define the width and depth of the channel when filled to the top of the bank as well as the channel length, slope along the channel length and Manning's "n" value. SWAT assumes the channel sides have a 2:1 run to rise ratio ($z_{ch} = 2$). The slope of the channel sides is then ½ or 0.5. The bottom width is calculated from the bankfull width and depth with the equation:

$$W_{btm} = W_{bnkfull} - 2 \cdot z_{ch} \cdot depth_{bnkfull} \qquad 23.1.1$$

where W_{btm} is the bottom width of the channel (m), $W_{bnkfull}$ is the top width of the channel when filled with water (m), z_{ch} is the inverse of the channel side slope, and $depth_{bnkfull}$ is the depth of water in the channel when filled to the top of the bank (m). Because of the assumption that $z_{ch} = 2$, it is possible for the bottom width calculated with equation 23.1.1 to be less than or equal to zero. If this occurs, the model sets $W_{btm} = 0.5 \cdot W_{bnkfull}$ and calculates a new value for the channel side slope run by solving equation 23.1.1 for z_{ch}:

$$z_{ch} = \frac{\left(W_{bnkfull} - W_{btm}\right)}{2 \cdot depth_{bnkfull}} \qquad 23.1.2$$

For a given depth of water in the channel, the width of the channel at water level is:

$$W = W_{btm} + 2 \cdot z_{ch} \cdot depth \qquad 23.1.3$$

where W is the width of the channel at water level (m), W_{btm} is the bottom width of the channel (m), z_{ch} is the inverse of the channel slope, and *depth* is the depth of water in the channel (m). The cross-sectional area of flow is calculated:

$$A_{ch} = (W_{btm} + z_{ch} \cdot depth) \cdot depth \qquad 23.1.4$$

where A_{ch} is the cross-sectional area of flow in the channel (m^2), W_{btm} is the bottom width of the channel (m), z_{ch} is the inverse of the channel slope, and *depth* is the depth of water in the channel (m). The wetted perimeter of the channel is defined as

$$P_{ch} = W_{btm} + 2 \cdot depth \cdot \sqrt{1 + z_{ch}^{2}} \qquad 23.1.5$$

where P_{ch} is the wetted perimeter for a given depth of flow (m). The hydraulic radius of the channel is calculated

$$R_{ch} = \frac{A_{ch}}{P_{ch}} \qquad 23.1.6$$

where R_{ch} is the hydraulic radius for a given depth of flow (m), A_{ch} is the cross-sectional area of flow in the channel (m^2), and P_{ch} is the wetted perimeter for a given depth of flow (m). The volume of water held in the channel is

$$V_{ch} = 1000 \cdot L_{ch} \cdot A_{ch} \qquad 23.1.7$$

where V_{ch} is the volume of water stored in the channel (m^3), L_{ch} is the channel length (km), and A_{ch} is the cross-sectional area of flow in the channel for a given depth of water (m^2).

When the volume of water in the reach exceeds the maximum amount that can be held by the channel, the excess water spreads across the flood plain. The flood plain dimensions used by SWAT are shown in Figure 23-2.

Figure 23-2: Illustration of flood plain dimensions.

The bottom width of the floodplain, $W_{btm,fld}$, is $W_{btm,fld} = 5 \cdot W_{bnkfull}$. SWAT assumes the flood plain side slopes have a 4:1 run to rise ratio ($z_{fld} = 4$). The slope of the flood plain sides is then ¼ or 0.25.

When flow is present in the flood plain, the calculation of the flow depth, cross-sectional flow area and wetting perimeter is a sum of the channel and floodplain components:

$$depth = depth_{bnkfull} + depth_{fld} \qquad 23.1.8$$

$$A_{ch} = \left(W_{btm} + z_{ch} \cdot depth_{bnkfull}\right) \cdot depth_{bnkfull} + \left(W_{btm,fld} + z_{fld} \cdot depth_{fld}\right) \cdot depth_{fld} \quad 23.1.9$$

$$P_{ch} = W_{btm} + 2 \cdot depth_{bnkfull} \cdot \sqrt{1 + z_{ch}^{\,2}} + 4 \cdot W_{bnkfull} + 2 \cdot depth_{fld} \cdot \sqrt{1 + z_{fld}^{\,2}} \qquad 23.1.10$$

where *depth* is the total depth of water (m), $depth_{bnkfull}$ is the depth of water in the channel when filled to the top of the bank (m), $depth_{fld}$ is the depth of water in the flood plain (m), A_{ch} is the cross-sectional area of flow for a given depth of water (m^2), W_{btm} is the bottom width of the channel (m), z_{ch} is the inverse of the channel side slope, $W_{btm,fld}$ is the bottom width of the flood plain (m), z_{fld} is the inverse of the flood plain side slope, P_{ch} is the wetted perimeter for a given depth of flow (m), and $W_{bnkfull}$ is the top width of the channel when filled with water (m).

Table 23-1: SWAT input variables that pertain to channel dimension calculations.

Variable name	Definition	File Name
CH_W(2)	$W_{bnkfull}$: Width of channel at top of bank (m)	.rte
CH_D	$depth_{bnkfull}$: Depth of water in channel when filled to bank (m)	.rte
CH_L(2)	L_{ch}: Length of main channel (km)	.rte

23.2 FLOW RATE AND VELOCITY

Manning's equation for uniform flow in a channel is used to calculate the rate and velocity of flow in a reach segment for a given time step:

$$q_{ch} = \frac{A_{ch} \cdot R_{ch}^{\,2/3} \cdot slp_{ch}^{\,1/2}}{n} \qquad 23.2.1$$

$$v_c = \frac{R_{ch}^{\,2/3} \cdot slp_{ch}^{\,1/2}}{n} \qquad 23.2.2$$

where q_{ch} is the rate of flow in the channel (m^3/s), A_{ch} is the cross-sectional area of flow in the channel (m^2), R_{ch} is the hydraulic radius for a given depth of flow (m),

slp_{ch} is the slope along the channel length (m/m), n is Manning's "n" coefficient for the channel, and v_c is the flow velocity (m/s).

SWAT routes water as a volume. The daily value for cross-sectional area of flow, A_{ch}, is calculated by rearranging equation 23.1.7 to solve for the area:

$$A_{ch} = \frac{V_{ch}}{1000 \cdot L_{ch}}$$ 23.2.3

where A_{ch} is the cross-sectional area of flow in the channel for a given depth of water (m^2), V_{ch} is the volume of water stored in the channel (m^3), and L_{ch} is the channel length (km). Equation 23.1.4 is rearranged to calculate the depth of flow for a given time step:

$$depth = \sqrt{\frac{A_{ch}}{z_{ch}} + \left(\frac{W_{btm}}{2 \cdot z_{ch}}\right)^2} - \frac{W_{btm}}{2 \cdot z_{ch}}$$ 23.2.4

where $depth$ is the depth of flow (m), A_{ch} is the cross-sectional area of flow in the channel for a given depth of water (m^2), W_{btm} is the bottom width of the channel (m), and z_{ch} is the inverse of the channel side slope. Equation 23.2.4 is valid only when all water is contained in the channel. If the volume of water in the reach segment has filled the channel and is in the flood plain, the depth is calculated:

$$depth = depth_{bnkfull} + \sqrt{\frac{\left(A_{ch} - A_{ch,bnkfull}\right)}{z_{fld}} + \left(\frac{W_{btm,fld}}{2 \cdot z_{fld}}\right)^2} - \frac{W_{btm,fld}}{2 \cdot z_{fld}}$$ 23.2.5

where $depth$ is the depth of flow (m), $depth_{bnkfull}$ is the depth of water in the channel when filled to the top of the bank (m), A_{ch} is the cross-sectional area of flow in the channel for a given depth of water (m^2), $A_{ch,bnkfull}$ is the cross-sectional area of flow in the channel when filled to the top of the bank (m^2), $W_{btm,fld}$ is the bottom width of the flood plain (m), and z_{fld} is the inverse of the flood plain side slope.

Once the depth is known, the wetting perimeter and hydraulic radius are calculated using equations 23.1.5 (or 23.1.10) and 23.1.6. At this point, all values required to calculate the flow rate and velocity are known and equations 23.2.1 and 23.2.2 can be solved.

Table 23-2: SWAT input variables that pertain to channel flow calculations.

Variable name	Definition	File Name
CH_S(2)	slp_{ch}: Average channel slope along channel length (m m^{-1})	.rte
CH_N(2)	n: Manning's "n" value for the main channel	.rte
CH_L(2)	L_{ch}: Length of main channel (km)	.rte

23.3 VARIABLE STORAGE ROUTING METHOD

The variable storage routing method was developed by Williams (1969) and used in the HYMO (Williams and Hann, 1973) and ROTO (Arnold et al., 1995) models.

For a given reach segment, storage routing is based on the continuity equation:

$$V_{in} - V_{out} = \Delta V_{stored}$$
$$\text{23.3.1}$$

where V_{in} is the volume of inflow during the time step (m^3 H$_2$O), V_{out} is the volume of outflow during the time step (m^3 H$_2$O), and ΔV_{stored} is the change in volume of storage during the time step (m^3 H$_2$O). This equation can be written as

$$\Delta t \cdot \left(\frac{q_{in,1} + q_{in,2}}{2} \right) - \Delta t \cdot \left(\frac{q_{out,1} + q_{out,2}}{2} \right) = V_{stored,2} - V_{stored,1}$$
$$\text{23.3.2}$$

where Δt is the length of the time step (s), $q_{in,1}$ is the inflow rate at the beginning of the time step (m^3/s), $q_{in,2}$ is the inflow rate at the end of the time step (m^3/s), $q_{out,1}$ is the outflow rate at the beginning of the time step (m^3/s), $q_{out,2}$ is the outflow rate at the end of the time step (m^3/s), $V_{stored,1}$ is the storage volume at the beginning of the time step (m^3 H$_2$O), and $V_{stored,2}$ is the storage volume at the end of the time step (m^3 H$_2$O). Rearranging equation 23.3.2 so that all known variables are on the left side of the equation,

$$q_{in,ave} + \frac{V_{stored,1}}{\Delta t} - \frac{q_{out,1}}{2} = \frac{V_{stored,2}}{\Delta t} + \frac{q_{out,2}}{2}$$
$$\text{23.3.3}$$

where $q_{in,ave}$ is the average inflow rate during the time step: $q_{in,ave} = \dfrac{q_{in,1} + q_{in,2}}{2}$.

Travel time is computed by dividing the volume of water in the channel by the flow rate.

$$TT = \frac{V_{stored}}{q_{out}} = \frac{V_{stored,1}}{q_{out,1}} = \frac{V_{stored,2}}{q_{out,2}} \qquad 23.3.4$$

where TT is the travel time (s), V_{stored} is the storage volume (m^3 H$_2$O), and q_{out} is the discharge rate (m^3/s).

To obtain a relationship between travel time and the storage coefficient, equation 23.3.4 is substituted into equation 23.3.3:

$$q_{in,ave} + \frac{V_{stored,1}}{\left(\frac{\Delta t}{TT}\right) \cdot \left(\frac{V_{stored,1}}{q_{out,1}}\right)} - \frac{q_{out,1}}{2} = \frac{V_{stored,2}}{\left(\frac{\Delta t}{TT}\right) \cdot \left(\frac{V_{stored,2}}{q_{out,2}}\right)} + \frac{q_{out,2}}{2} \qquad 23.3.5$$

which simplifies to

$$q_{out,2} = \left(\frac{2 \cdot \Delta t}{2 \cdot TT + \Delta t}\right) \cdot q_{in,ave} + \left(1 - \frac{2 \cdot \Delta t}{2 \cdot TT + \Delta t}\right) \cdot q_{out,1} \qquad 23.3.6$$

This equation is similar to the coefficient method equation

$$q_{out,2} = SC \cdot q_{in,ave} + (1 - SC) \cdot q_{out,1} \qquad 23.3.7$$

where SC is the storage coefficient. Equation 23.3.7 is the basis for the SCS convex routing method (SCS, 1964) and the Muskingum method (Brakensiek, 1967; Overton, 1966). From equation 23.3.6, the storage coefficient in equation 23.3.7 is defined as

$$SC = \frac{2 \cdot \Delta t}{2 \cdot TT + \Delta t} \qquad 23.3.8$$

It can be shown that

$$(1 - SC) \cdot q_{out} = SC \cdot \frac{V_{stored}}{\Delta t} \qquad 23.3.9$$

Substituting this into equation 23.3.7 gives

$$q_{out,2} = SC \cdot \left(q_{in,ave} + \frac{V_{stored,1}}{\Delta t}\right) \qquad 23.3.10$$

To express all values in units of volume, both sides of the equation are multiplied by the time step

$$V_{out,2} = SC \cdot \left(V_{in} + V_{stored,1}\right) \qquad 23.3.11$$

23.4 MUSKINGUM ROUTING METHOD

The Muskingum routing method models the storage volume in a channel length as a combination of wedge and prism storages (Figure 23-3).
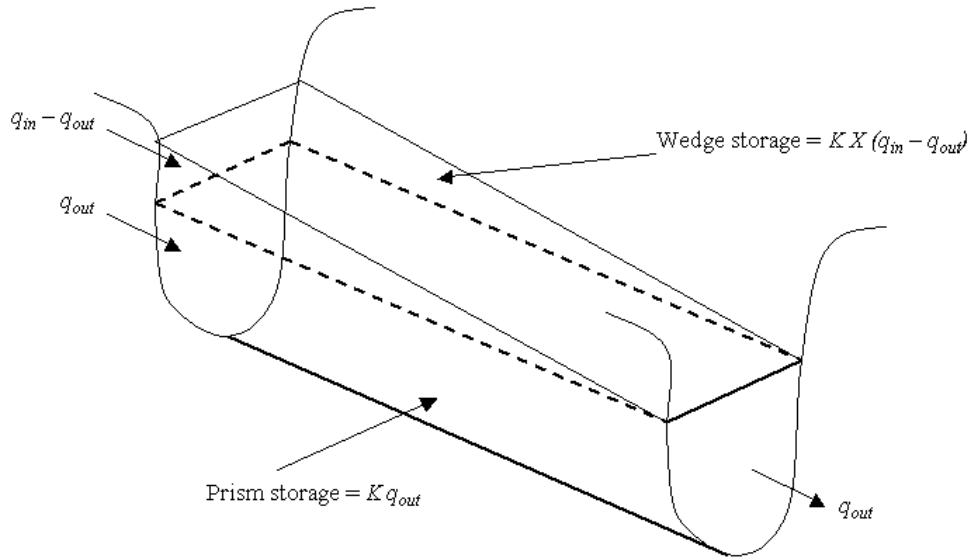

Figure 23-3: Prism and wedge storages in a reach segment (from Chow et al., 1988)

When a flood wave advances into a reach segment, inflow exceeds outflow and a wedge of storage is produced. As the flood wave recedes, outflow exceeds inflow in the reach segment and a negative wedge is produced. In addition to the wedge storage, the reach segment contains a prism of storage formed by a volume of constant cross-section along the reach length.

As defined by Manning's equation (equation 23.2.1), the cross-sectional area of flow is assumed to be directly proportional to the discharge for a given reach segment. Using this assumption, the volume of prism storage can be expressed as a function of the discharge, $K \cdot q_{out}$, where K is the ratio of storage to discharge and has the dimension of time. In a similar manner, the volume of wedge storage can be expressed as $K \cdot X \cdot (q_{in} - q_{out})$, where X is a weighting factor that controls the relative importance of inflow and outflow in determining the storage in a reach. Summing these terms gives a value for total storage

$$V_{stored} = K \cdot q_{out} + K \cdot X \cdot (q_{in} - q_{out}) \qquad 23.4.1$$

where V_{stored} is the storage volume (m^3 H$_2$O), q_{in} is the inflow rate (m^3/s), q_{out} is the discharge rate (m^3/s), K is the storage time constant for the reach (s), and X is the weighting factor. This equation can be rearranged to the form

$$V_{stored} = K \cdot \left(X \cdot q_{in} + (1 - X) \cdot q_{out} \right) \qquad 23.4.2$$

This format is similar to equation 23.3.7.

The weighting factor, X, has a lower limit of 0.0 and an upper limit of 0.5. This factor is a function of the wedge storage. For reservoir-type storage, there is no wedge and $X = 0.0$. For a full-wedge, $X = 0.5$. For rivers, X will fall between 0.0 and 0.3 with a mean value near 0.2.

The definition for storage volume in equation 23.4.2 can be incorporated into the continuity equation (equation 23.3.2) and simplified to

$$q_{out,2} = C_1 \cdot q_{in,2} + C_2 \cdot q_{in,1} + C_3 \cdot q_{out,1} \qquad 23.4.3$$

where $q_{in,1}$ is the inflow rate at the beginning of the time step (m^3/s), $q_{in,2}$ is the inflow rate at the end of the time step (m^3/s), $q_{out,1}$ is the outflow rate at the beginning of the time step (m^3/s), $q_{out,2}$ is the outflow rate at the end of the time step (m^3/s), and

$$C_1 = \frac{\Delta t - 2 \cdot K \cdot X}{2 \cdot K \cdot (1 - X) + \Delta t} \qquad 23.4.4$$

$$C_2 = \frac{\Delta t + 2 \cdot K \cdot X}{2 \cdot K \cdot (1 - X) + \Delta t} \qquad 23.4.5$$

$$C_3 = \frac{2 \cdot K \cdot (1 - X) - \Delta t}{2 \cdot K \cdot (1 - X) + \Delta t} \qquad 23.4.6$$

where $C_1 + C_2 + C_3 = 1$. To express all values in units of volume, both sides of equation 23.4.3 are multiplied by the time step

$$V_{out,2} = C_1 \cdot V_{in,2} + C_2 \cdot V_{in,1} + C_3 \cdot V_{out,1} \qquad 23.4.7$$

To maintain numerical stability and avoid the computation of negative outflows, the following condition must be met:

$$2 \cdot K \cdot X < \Delta t < 2 \cdot K \cdot (1 - X) \qquad 23.4.8$$

The value for the weighting factor, X, is input by the user. The value for the storage time constant is estimated as:

$$K = coef_1 \cdot K_{bnkfull} + coef_2 \cdot K_{0.1bnkfull} \qquad\qquad 23.4.9$$

where K is the storage time constant for the reach segment (s), $coef_1$ and $coef_2$ are weighting coefficients input by the user, $K_{bnkfull}$ is the storage time constant calculated for the reach segment with bankfull flows (s), and $K_{0.1bnkfull}$ is the storage time constant calculated for the reach segment with one-tenth of the bankfull flows (s). To calculate $K_{bnkfull}$ and $K_{0.1bnkfull}$, an equation developed by Cunge (1969) is used:

$$K = \frac{1000 \cdot L_{ch}}{c_k} \qquad\qquad 23.4.10$$

where K is the storage time constant (s), L_{ch} is the channel length (km), and c_k is the celerity corresponding to the flow for a specified depth (m/s). Celerity is the velocity with which a variation in flow rate travels along the channel. It is defined as

$$c_k = \frac{d}{dA_{ch}}(q_{ch}) \qquad\qquad 23.4.11$$

where the flow rate, q_{ch}, is defined by Manning's equation. Differentiating equation 23.2.1 with respect to the cross-sectional area gives

$$c_k = \frac{5}{3} \cdot \left(\frac{R_{ch}^{2/3} \cdot slp_{ch}^{1/2}}{n} \right) = \frac{5}{3} \cdot v_c \qquad\qquad 23.4.12$$

where c_k is the celerity (m/s), R_{ch} is the hydraulic radius for a given depth of flow (m), slp_{ch} is the slope along the channel length (m/m), n is Manning's "n" coefficient for the channel, and v_c is the flow velocity (m/s).

Table 23-3: SWAT input variables that pertain to Muskingum routing.

Variable name	Definition	File Name
MSK_X	X: weighting factor	.bsn
MSK_CO1	$coef_1$: weighting factor for influence of normal flow on storage time constant value	.bsn
MSK_CO2	$coef_2$: weighting factor for influence of low flow on storage time constant	.bsn

23.5 TRANSMISSION LOSSES

The classification of a stream as ephemeral, intermittent or perennial is a function of the amount of groundwater contribution received by the stream. Ephemeral streams contain water during and immediately after a storm event and are dry the rest of the year. Intermittent streams are dry part of the year, but contain flow when the groundwater is high enough as well as during and after a storm event. Perennial streams receive continuous groundwater contributions and flow throughout the year.

During periods when a stream receives no groundwater contributions, it is possible for water to be lost from the channel via transmission through the side and bottom of the channel. Transmission losses are estimated with the equation

$$tloss = K_{ch} \cdot TT \cdot P_{ch} \cdot L_{ch} \qquad\qquad 23.5.1$$

where *tloss* are the channel transmission losses (m^3 H$_2$O), K_{ch} is the effective hydraulic conductivity of the channel alluvium (mm/hr), TT is the flow travel time (hr), P_{ch} is the wetted perimeter (m), and L_{ch} is the channel length (km). Transmission losses from the main channel are assumed to enter bank storage or the deep aquifer.

Typical values for K_{ch} for various alluvium materials are given in Table 23-4. For perennial streams with continuous groundwater contribution, the effective conductivity will be zero.

Table 23-4: Example hydraulic conductivity values for various bed materials (from Lane, 1983).

Bed material group	Bed material characteristics	Hydraulic conductivity
1 Very high loss rate	Very clean gravel and large sand	> 127 mm/hr
2 High loss rate	Clean sand and gravel, field conditions	51-127 mm/hr
3 Moderately high loss rate	Sand and gravel mixture with low silt-clay content	25-76 mm/hr
4 Moderate loss rate	Sand and gravel mixture with high silt-clay content	6-25 mm/hr
5 Insignificant to low loss rate	Consolidated bed material; high silt-clay content	0.025-2.5 mm/hr

Table 23-5: SWAT input variables that pertain to transmission losses.

Variable name	Definition	File Name
CH_K(2)	K_{ch}: Effective hydraulic conductivity of channel (mm/hr)	.rte
CH_L(2)	L_{ch}: Length of main channel (km)	.rte

23.6 EVAPORATION LOSSES

Evaporation losses from the reach are calculated:

$$E_{ch} = coef_{ev} \cdot E_o \cdot L_{ch} \cdot W \cdot fr_{\Delta t} \qquad\qquad 23.6.1$$

where E_{ch} is the evaporation from the reach for the day (m^3 H$_2$O), $coef_{ev}$ is an evaporation coefficient, E_o is potential evaporation (mm H$_2$O), L_{ch} is the channel length (km), W is the channel width at water level (m), and $fr_{\Delta t}$ is the fraction of the time step in which water is flowing in the channel.

The evaporation coefficient is a calibration parameter for the user and is allowed to vary between 0.0 and 1.0.

The fraction of the time step in which water is flowing in the channel is calculated by dividing the travel time by the length of the time step.

Table 23-6: SWAT input variables that pertain to evaporation losses.

Variable name	Definition	File Name
EVRCH	$coef_{ev}$: Reach evaporation adjustment factor	.bsn
CH_L(2)	L_{ch}: Length of main channel (km)	.rte

23.7 BANK STORAGE

The amount of water entering bank storage on a given day is calculated:

$$bnk_{in} = tloss \cdot \left(1 - fr_{trns}\right) \qquad\qquad 23.7.1$$

where bnk_{in} is the amount of water entering bank storage (m^3 H$_2$O), $tloss$ are the channel transmission losses (m^3 H$_2$O), and fr_{trns} is the fraction of transmission losses partitioned to the deep aquifer.

Bank storage contributes flow to the main channel or reach within the subbasin. Bank flow is simulated with a recession curve similar to that used for groundwater. The volume of water entering the reach from bank storage is calculated:

$$V_{bnk} = bnk \cdot (1 - \alpha_{bnk})$$ 23.7.2

where V_{bnk} is the volume of water added to the reach via return flow from bank storage (m³ H₂O), bnk is the total amount of water in bank storage (m³ H₂O), and α_{bnk} is the bank flow recession constant or constant of proportionality.

Water may move from bank storage into an adjacent unsaturated zone. SWAT models the movement of water into adjacent unsaturated areas as a function of water demand for evapotranspiration. To avoid confusion with soil evaporation and transpiration, this process has been termed 'revap'. This process is significant in watersheds where the saturated zone is not very far below the surface or where deep-rooted plants are growing. 'Revap' from bank storage is governed by the groundwater revap coefficient defined for the last HRU in the subbasin.

The maximum amount of water than will be removed from bank storage via 'revap' on a given day is:

$$bnk_{revap,mx} = \beta_{rev} \cdot E_o \cdot L_{ch} \cdot W$$ 23.7.3

where $bnk_{revap,mx}$ is the maximum amount of water moving into the unsaturated zone in response to water deficiencies (m³ H₂O), β_{rev} is the revap coefficient, E_o is the potential evapotranspiration for the day (mm H₂O), L_{ch} is the channel length (km), and W is the width of the channel at water level (m). The actual amount of revap that will occur on a given day is calculated:

$$bnk_{revap} = bnk \qquad \qquad \text{if } bnk < bnk_{revap,mx}$$ 23.7.4

$$bnk_{revap} = bnk_{revap,mx} \qquad \qquad \text{if } bnk \geq bnk_{revap,mx}$$ 23.7.5

where bnk_{revap} is the actual amount of water moving into the unsaturated zone in response to water deficiencies (m³ H₂O), $bnk_{revap,mx}$ is the maximum amount of water moving into the unsaturated zone in response to water deficiencies (m³ H₂O), and bnk is the amount of water in bank storage at the beginning of day i (m³ H₂O).

Table 23-7: SWAT input variables that pertain to bank storage.

Variable name	Definition	File Name
TRNSRCH	fr_{trns}: Fraction of transmission losses partitioned to the deep aquifer	.bsn
ALPHA_BNK	α_{bnk}: Bank flow recession constant or constant of proportionality	.rte
GW_REVAP	β_{rev}: Revap coefficient	.gw

23.8 CHANNEL WATER BALANCE

Water storage in the reach at the end of the time step is calculated:

$$V_{stored,2} = V_{stored,1} + V_{in} - V_{out} - tloss - E_{ch} + div + V_{bnk} \qquad 23.8.1$$

where $V_{stored,2}$ is the volume of water in the reach at the end of the time step (m^3 H$_2$O), $V_{stored,1}$ is the volume of water in the reach at the beginning of the time step (m^3 H$_2$O), V_{in} is the volume of water flowing into the reach during the time step (m^3 H$_2$O), V_{out} is the volume of water flowing out of the reach during the time step (m^3 H$_2$O), $tloss$ is the volume of water lost from the reach via transmission through the bed (m^3 H$_2$O), E_{ch} is the evaporation from the reach for the day (m^3 H$_2$O), div is the volume of water added or removed from the reach for the day through diversions (m^3 H$_2$O), and V_{bnk} is the volume of water added to the reach via return flow from bank storage (m^3 H$_2$O).

SWAT treats the volume of outflow calculated with equation 23.3.11 or 23.4.7 as the net amount of water removed from the reach. As transmission losses, evaporation and other water losses for the reach segment are calculated, the amount of outflow to the next reach segment is reduced by the amount of the loss. When outflow and all losses are summed, the total amount will equal the value obtained from 23.3.11 or 23.4.7.

23.9 NOMENCLATURE

A_{ch} Cross-sectional area of flow in the channel (m^2)

$A_{ch,bnkfull}$ Cross-sectional area of flow in the channel when filled to the top of the bank (m^2)

C_1 Coefficient in Muskingum flood routing equation

C_2 Coefficient in Muskingum flood routing equation

C_3 Coefficient in Muskingum flood routing equation

E_{ch} Evaporation from the reach for the day (m^3 H_2O)

E_o Potential evapotranspiration (mm d^{-1})

K Storage time constant for the reach (s)

$K_{0.1bnkfull}$ Storage time constant calculated for the reach segment with one-tenth of the bankfull flows (s)

$K_{bnkfull}$ Storage time constant calculated for the reach segment with bankfull flows (s)

K_{ch} Effective hydraulic conductivity of the channel alluvium (mm/hr)

L_{ch} Length of main channel (km)

P_{ch} Wetted perimeter for a given depth of flow (m)

R_{ch} Hydraulic radius for a given depth of flow (m)

SC Storage coefficient for variable storage flow routing

TT Travel time (s)

V_{bnk} Volume of water added to the reach via return flow from bank storage (m^3 H_2O)

V_{ch} Volume of water stored in the channel (m^3)

V_{in} Volume of inflow during the time step (m^3 H_2O)

V_{out} Volume of outflow during the time step (m^3 H_2O)

V_{stored} Volume of water stored in water body or channel (m^3 H_2O)

W Width of channel at water level (m)

$W_{bnkfull}$ Top width of the channel when filled with water (m)

W_{btm} Bottom width of the channel (m)

$W_{btm,fld}$ Bottom width of the flood plain (m)

X Weighting factor in Muskingum routing

bnk Total amount of water in bank storage (m^3 H_2O)

bnk_{in} Amount of water entering bank storage (m^3 H_2O)

$bnk_{revap,mx}$ Maximum amount of water moving into the unsaturated zone in response to water deficiencies (m^3 H_2O)

c_k Celerity corresponding to the flow for a specified depth (m/s)

$coef_1$ Weighting coefficient for storage time constant calculation

$coef_2$ Weighting coefficient for storage time constant calculation

$coef_{ev}$ Evaporation coefficient

$depth$ Depth of water in the channel (m)

$depth_{bnkfull}$ Depth of water in the channel when filled to the top of the bank (m)

$depth_{fld}$ Depth of water in the flood plain (m)

div Volume of water added or removed from the reach for the day through diversions (m^3 H_2O)

fr_{trns} Fraction of transmission losses partitioned to the deep aquifer

$fr_{\Delta t}$ Fraction of the time step in which water is flowing in the channel
n Manning's roughness coefficient for the subbasin or channel
q_{ch} Average channel flow rate (m^3 s^{-1})
q_{in} Inflow rate (m^3/s)
q_{out} Outflow rate (m^3/s)
slp_{ch} Average channel slope along channel length (m m^{-1})
$tloss$ Channel transmission losses (m^3 H$_2$O)
v_c Average channel velocity (m s^{-1})
z_{ch} Inverse of the channel side slope
z_{fld} Inverse of the flood plain side slope

α_{bnk} Bank flow recession constant or constant of proportionality
β_{rev} Revap coefficient
Δt Length of the time step (s)

23.10 REFERENCES

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CHAPTER 24

EQUATIONS: SEDIMENT ROUTING

Sediment transport in the channel network is a function of two processes, deposition and degradation, operating simultaneously in the reach. SWAT will compute deposition and degradation using the same channel dimensions for the entire simulation. Alternatively, SWAT will simulate downcutting and widening of the stream channel and update channel dimensions throughout the simulation.

24.1 SEDIMENT CHANNEL ROUTING

Previous versions of SWAT used stream power to predict degradation and fall velocity to estimate deposition in the channels (Arnold et al, 1995). Williams (1980) used Bagnold's (1977) definition of stream power to develop a method for determining degradation as a function of channel slope and velocity. In this version, the equations have been simplified and the maximum amount of sediment that can be transported from a reach segment is a function of the peak channel velocity. The peak channel velocity, $v_{ch,pk}$, is calculated:

$$v_{ch,pk} = \frac{q_{ch,pk}}{A_{ch}}$$
24.1.1

where $q_{ch,pk}$ is the peak flow rate (m³/s) and A_{ch} is the cross-sectional area of flow in the channel (m²). The peak flow rate is defined as:

$$q_{ch,pk} = prf \cdot q_{ch}$$
24.1.2

where prf is the peak rate adjustment factor, and q_{ch} is the average rate of flow (m³/s). Calculation of the average rate of flow, q_{ch}, and the cross-sectional area of flow, A_{ch}, is reviewed in Chapter 23.

The maximum amount of sediment that can be transported from a reach segment is calculated:

$$conc_{sed,ch,mx} = c_{sp} \cdot v_{ch,pk}^{spexp}$$
24.1.3

where $conc_{sed,ch,mx}$ is the maximum concentration of sediment that can be transported by the water (ton/m³ or kg/L), c_{sp} is a coefficient defined by the user, $v_{ch,pk}$ is the peak channel velocity (m/s), and $spexp$ is an exponent defined by the user. The exponent, $spexp$, normally varies between 1.0 and 2.0 and was set at 1.5 in the original Bagnold stream power equation (Arnold et al., 1995).

The maximum concentration of sediment calculated with equation 24.1.3 is compared to the concentration of sediment in the reach at the beginning of the time step, $conc_{sed,ch,i}$. If $conc_{sed,ch,i} > conc_{sed,ch,mx}$, deposition is the dominant process in the reach segment and the net amount of sediment deposited is calculated:

$$sed_{dep} = \left(conc_{sed,ch,i} - conc_{sed,ch,mx}\right) \cdot V_{ch} \qquad\qquad 24.1.4$$

where sed_{dep} is the amount of sediment deposited in the reach segment (metric tons), $conc_{sed,ch,i}$ is the initial sediment concentration in the reach (kg/L or ton/m^3), $conc_{sed,ch,mx}$ is the maximum concentration of sediment that can be transported by the water (kg/L or ton/m^3), and V_{ch} is the volume of water in the reach segment (m^3 H$_2$O).

If $conc_{sed,ch,i} < conc_{sed,ch,mx}$, degradation is the dominant process in the reach segment and the net amount of sediment reentrained is calculated:

$$sed_{deg} = \left(conc_{sed,ch,mx} - conc_{sed,ch,i}\right) \cdot V_{ch} \cdot K_{CH} \cdot C_{CH} \qquad 24.1.5$$

where sed_{deg} is the amount of sediment reentrained in the reach segment (metric tons), $conc_{sed,ch,mx}$ is the maximum concentration of sediment that can be transported by the water (kg/L or ton/m^3), $conc_{sed,ch,i}$ is the initial sediment concentration in the reach (kg/L or ton/m^3), V_{ch} is the volume of water in the reach segment (m^3 H$_2$O), K_{CH} is the channel erodibility factor (cm/hr/Pa), and C_{CH} is the channel cover factor.

Once the amount of deposition and degradation has been calculated, the final amount of sediment in the reach is determined:

$$sed_{ch} = sed_{ch,i} - sed_{dep} + sed_{deg} \qquad\qquad 24.1.6$$

where sed_{ch} is the amount of suspended sediment in the reach (metric tons), $sed_{ch,i}$ is the amount of suspended sediment in the reach at the beginning of the time period (metric tons), sed_{dep} is the amount of sediment deposited in the reach segment (metric tons), and sed_{deg} is the amount of sediment reentrained in the reach segment (metric tons).

The amount of sediment transported out of the reach is calculated:

$$sed_{out} = sed_{ch} \cdot \frac{V_{out}}{V_{ch}} \qquad\qquad 24.1.7$$

where sed_{out} is the amount of sediment transported out of the reach (metric tons), sed_{ch} is the amount of suspended sediment in the reach (metric tons), V_{out} is the volume of outflow during the time step (m^3 H$_2$O), and V_{ch} is the volume of water in the reach segment (m^3 H$_2$O).

24.1.1 CHANNEL ERODIBILITY FACTOR

The channel erodibility factor is conceptually similar to the soil erodibility factor used in the USLE equation. Channel erodibility is a function of properties of the bed or bank materials.

Channel erodibility can be measured with a submerged vertical jet device. The basic premise of the test is that erosion of a vegetated or bare channel and local scour beneath an impinging jet are the result of hydraulic stresses, boundary geometry, and the properties of the material being eroded. Hanson (1990) developed a method for determining the erodibility coefficient of channels *in situ* with the submerged vertical jet. Allen et al. (1999) utilized this method to determine channel erodibility factors for thirty sites in Texas.

A submerged, vertical jet of water directed perpendicularly at the channel bed causes erosion of the bed material in the vicinity of the jet impact area (Figure 24-1). Important variables in the erosion process are: the volume of material removed during a jetting event, elevation of the jet above the ground surface, diameter of the jet nozzle, jet velocity, time, mass density of the fluid and coefficient of erodibility.
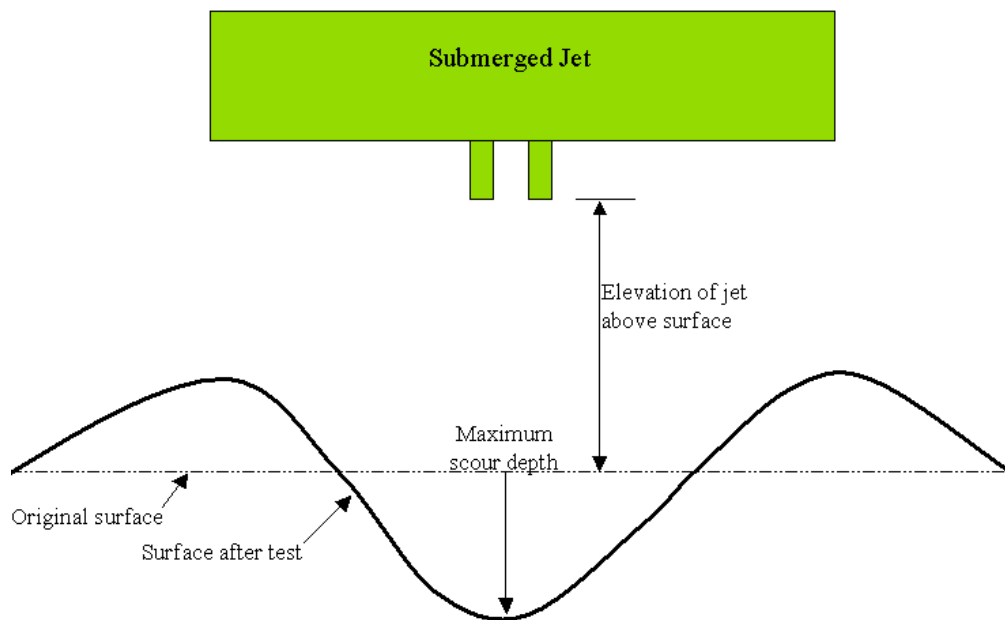

Figure 24-1: Simplified cross-section of submerged jet test.

Hanson (1991) defined a jet index, J_i, to relate erodibility to scour created by the submerged jet. The jet index is a function of the depth of scour beneath the jet per unit time and the jet velocity. The jet index is determined by a least squares fit following the procedures outlined in ASTM standard D 5852-95.

Once the jet index is determined, the channel erodibility coefficient is calculated:

$$K_{CH} = 0.003 \cdot \exp[385 \cdot J_i]$$ 24.1.8

where K_{CH} is the channel erodibility coefficient (cm/h/Pa) and J_i is the jet index. In general, values for channel erodibility are an order of magnitude smaller than values for soil erodibility.

24.1.2 CHANNEL COVER FACTOR

The channel cover factor, C_{CH}, is defined as the ratio of degradation from a channel with a specified vegetative cover to the corresponding degradation from a channel with no vegetative cover. The vegetation affects degradation by reducing the stream velocity, and consequently its erosive power, near the bed surface.

Table 24-1: SWAT input variables that pertain to sediment routing.

Variable Name	Definition	Input File
PRF	prf: Peak rate adjustment factor	.bsn
SPCON	c_{sp}: Coefficient in sediment transport equation	.bsn
SPEXP	$spexp$: Exponent in sediment transport equation	.bsn
CH_COV	C_{CH}: Channel cover factor	.rte
CH_EROD	K_{CH}: Channel erodibility factor (cm/hr/Pa)	.rte

24.2 CHANNEL DOWNCUTTING AND WIDENING

While sediment transport calculations have traditionally been made with the same channel dimensions throughout a simulation, SWAT will model channel downcutting and widening. When channel downcutting and widening is simulated, channel dimensions are allowed to change during the simulation period.

Three channel dimensions are allowed to vary in channel downcutting and widening simulations: bankfull depth, $depth_{bnkfull}$, channel width, $W_{bnkfull}$, and

channel slope, slp_{ch}. Channel dimensions are updated using the following equations when the volume of water in the reach exceeds 1.4×10^6 m^3.

The amount of downcutting is calculated (Allen et al., 1999):

$$depth_{dcut} = 358 \cdot depth \cdot slp_{ch} \cdot K_{CH} \qquad\qquad 24.2.1$$

where $depth_{dcut}$ is the amount of downcutting (m), $depth$ is the depth of water in channel (m), slp_{ch} is the channel slope (m/m), and K_{CH} is the channel erodibility coefficient (cm/h/Pa).

The new bankfull depth is calculated:

$$depth_{bnkfull} = depth_{bnkfull,i} + depth_{dcut} \qquad\qquad 24.2.2$$

where $depth_{bnkfull}$ is the new bankfull depth (m), $depth_{bnkfull,i}$ is the previous bankfull depth, and $depth_{dcut}$ is the amount of downcutting (m).

The new bank width is calculated:

$$W_{bnkfull} = ratio_{WD} \cdot depth_{bnkfull} \qquad\qquad 24.2.3$$

where $W_{bnkfull}$ is the new width of the channel at the top of the bank (m), $ratio_{WD}$ is the channel width to depth ratio, and $depth_{bnkfull}$ is the new bankfull depth (m).

The new channel slope is calculated:

$$slp_{ch} = slp_{ch,i} - \frac{depth_{dcut}}{1000 \cdot L_{ch}} \qquad\qquad 24.2.4$$

where slp_{ch} is the new channel slope (m/m), $slp_{ch,i}$ is the previous channel slope (m/m), $depth_{bnkfull}$ is the new bankfull depth (m), and L_{ch} is the channel length (km).

Table 24-2: SWAT input variables that pertain to channel downcutting and widening.

Variable Name	Definition	Input File
IDEG	Channel degradation code	.cod
CH_WDR	$ratio_{WD}$: Channel width to depth ratio	.rte

24.3 NOMENCLATURE

A_{ch} Cross-sectional area of flow in the channel (m^2)
C_{CH} Channel cover factor
J_i Jet index used to calculate channel erodibility
K_{CH} Channel erodibility factor (cm/hr/Pa)
L_{ch} Channel length (km)
V_{ch} Volume of water in the reach segment (m^3 H_2O)
V_{out} Volume of outflow during the time step (m^3 H_2O)
$W_{bnkfull}$ Top width of the channel when filled with water (m)

c_{sp} Coefficient in sediment transport equation
$conc_{sed,ch,i}$ Initial sediment concentration in the reach (kg/L or ton/m^3)
$conc_{sed,ch,mx}$ Maximum concentration of sediment that can be transported by the water
          (kg/L or ton/m^3)
$depth$ Depth of water in channel (m)
$depth_{bnkfull}$ Depth of water in the channel when filled to the top of the bank (m)
$depth_{dcut}$ Amount of downcutting (m)
prf Peak rate adjustment factor
q_{ch} Average rate of flow in the channel (m^3/s)
$q_{ch,pk}$ Peak flow rate (m^3/s)
$ratio_{WD}$ Channel width to depth ratio
sed_{ch} Amount of suspended sediment in the reach (metric tons)
sed_{deg} Amount of sediment reentrained in the reach segment (metric tons)
sed_{dep} Amount of sediment deposited in the reach segment (metric tons)
sed_{out} Amount of sediment transported out of the reach (metric tons)
slp_{ch} Average channel slope along channel length (m m^{-1})
$spexp$ Exponent in sediment transport equation
$v_{ch,pk}$ Peak channel velocity (m/s)

24.4 REFERENCES

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CHAPTER **25**

EQUATIONS: IN-STREAM NUTRIENT PROCESSES

Parameters which affect water quality and can be considered pollution indicators include nutrients, total solids, biological oxygen demand, nitrates, and microorganisms (Loehr, 1970; Paine, 1973). Parameters of secondary importance include odor, taste, and turbidity (Azevedo and Stout, 1974).

The SWAT in-stream water quality algorithms incorporate constituent interactions and relationships used in the QUAL2E model (Brown and Barnwell, 1987). The documentation provided in this chapter has been taken from Brown

and Barnwell (1987). The modeling of in-stream nutrient transformations has been made an optional feature of SWAT. To route nutrient loadings downstream without simulating transformations, the variable IWQ in the input control code (.cod) file should be set to 0. To activate the simulation of in-stream nutrient transformations, this variable should be set to 1.

25.1 ALGAE

During the day, algae increase the stream's dissolved oxygen concentration via photosynthesis. At night, algae reduce the concentration via respiration. As algae grow and die, they form part of the in-stream nutrient cycle. This section summarizes the equations used to simulate algal growth in the stream.

25.1.1 CHLOROPHYLL *a*

Chlorophyll *a* is assumed to be directly proportional to the concentration of phytoplanktonic algal biomass.

$$chla = \alpha_0 \cdot algae \qquad\qquad 25.1.1$$

where *chla* is the chlorophyll *a* concentration (µg chla/L), α_0 is the ratio of chlorophyll *a* to algal biomass (µg chla/mg alg), and *algae* is the algal biomass concentration (mg alg/L).

25.1.2 ALGAL GROWTH

Growth and decay of algae/chlorophyll *a* is calculated as a function of the growth rate, the respiration rate, the settling rate and the amount of algae present in the stream. The change in algal biomass for a given day is:

$$\Delta algae = \left((\mu_a \cdot algae) - (\rho_a \cdot algae) - \left(\frac{\sigma_1}{depth} \cdot algae \right) \right) \cdot TT \qquad 25.1.2$$

where $\Delta algae$ is the change in algal biomass concentration (mg alg/L), μ_a is the local specific growth rate of algae (day^{-1}), ρ_a is the local respiration or death rate of algae (day^{-1}), σ_1 is the local settling rate for algae (m/day), *depth* is the depth of water in the channel (m), *algae* is the algal biomass concentration at the beginning

of the day (mg alg/L), and *TT* is the flow travel time in the reach segment (day). The calculation of depth and travel time are reviewed in Chapter 23.

25.1.2.1 LOCAL SPECIFIC GROWTH RATE OF ALGAE

The local specific growth rate of algae is a function of the availability of required nutrients, light and temperature. SWAT first calculates the growth rate at 20°C and then adjusts the growth rate for water temperature. The user has three options for calculating the impact of nutrients and light on growth: multiplicative, limiting nutrient, and harmonic mean.

The multiplicative option multiplies the growth factors for light, nitrogen and phosphorus together to determine their net effect on the local algal growth rate. This option has its biological basis in the mutiplicative effects of enzymatic processes involved in photosynthesis:

$$\mu_{a,20} = \mu_{max} \cdot FL \cdot FN \cdot FP \qquad\qquad 25.1.3$$

where $\mu_{a,20}$ is the local specific algal growth rate at 20°C (day^{-1}), μ_{max} is the maximum specific algal growth rate (day^{-1}), *FL* is the algal growth attenuation factor for light, *FN* is the algal growth limitation factor for nitrogen, and *FP* is the algal growth limitation factor for phosphorus. The maximum specific algal growth rate is specified by the user.

The limiting nutrient option calculates the local algal growth rate as limited by light and either nitrogen or phosphorus. The nutrient/light effects are multiplicative, but the nutrient/nutrient effects are alternate. The algal growth rate is controlled by the nutrient with the smaller growth limitation factor. This approach mimics Liebig's law of the minimum:

$$\mu_{a,20} = \mu_{max} \cdot FL \cdot \min(FN, \quad FP) \qquad\qquad 25.1.4$$

where $\mu_{a,20}$ is the local specific algal growth rate at 20°C (day^{-1}), μ_{max} is the maximum specific algal growth rate (day^{-1}), *FL* is the algal growth attenuation factor for light, *FN* is the algal growth limitation factor for nitrogen, and *FP* is the algal growth limitation factor for phosphorus. The maximum specific algal growth rate is specified by the user.

The harmonic mean is mathematically analogous to the total resistance of two resistors in parallel and can be considered a compromise between equations 25.1.3 and 25.1.4. The algal growth rate is controlled by a multiplicative relation between light and nutrients, while the nutrient/nutrient interactions are represented by a harmonic mean.

$$\mu_{a,20} = \mu_{max} \cdot FL \cdot \frac{2}{\left(\dfrac{1}{FN} + \dfrac{1}{FP}\right)} \qquad 25.1.5$$

where $\mu_{a,20}$ is the local specific algal growth rate at 20°C (day^{-1}), μ_{max} is the maximum specific algal growth rate (day^{-1}), FL is the algal growth attenuation factor for light, FN is the algal growth limitation factor for nitrogen, and FP is the algal growth limitation factor for phosphorus. The maximum specific algal growth rate is specified by the user.

Calculation of the growth limiting factors for light, nitrogen and phosphorus are reviewed in the following sections.

ALGAL GROWTH LIMITING FACTOR FOR LIGHT.

A number of mathematical relationships between photosynthesis and light have been developed. All relationships show an increase in photosynthetic rate with increasing light intensity up to a maximum or saturation value. The algal growth limiting factor for light is calculated using a Monod half-saturation method. In this option, the algal growth limitation factor for light is defined by a Monod expression:

$$FL_z = \frac{I_{phosyn,z}}{K_L + I_{phosyn,z}} \qquad 25.1.6$$

where FL_z is the algal growth attenuation factor for light at depth z, $I_{phosyn,z}$ is the photosynthetically-active light intensity at a depth z below the water surface (MJ/m^2-hr), and K_L is the half-saturation coefficient for light (MJ/m^2-hr). Photosynthetically-active light is radiation with a wavelength between 400 and 700 nm. The half-saturation coefficient for light is defined as the light intensity at

which the algal growth rate is 50% of the maximum growth rate. The half-saturation coefficient for light is defined by the user.

Photosynthesis is assumed to occur throughout the depth of the water column. The variation in light intensity with depth is defined by Beer's law:

$$I_{phosyn,z} = I_{phosyn,hr} \exp(-k_\ell \cdot z) \qquad\qquad 25.1.7$$

where $I_{phosyn,z}$ is the photosynthetically-active light intensity at a depth z below the water surface (MJ/m^2-hr), $I_{phosyn,hr}$ is the photosynthetically-active solar radiation reaching the ground/water surface during a specific hour on a given day (MJ/m^2-hr), k_ℓ is the light extinction coefficient (m^{-1}), and z is the depth from the water surface (m). Substituting equation 25.1.7 into equation 25.1.6 and integrating over the depth of flow gives:

$$FL = \left(\frac{1}{k_\ell \cdot depth}\right) \cdot \ln\left[\frac{K_L + I_{phosyn,hr}}{K_L + I_{phosyn,hr} \exp(-k_\ell \cdot depth)}\right] \qquad 25.1.8$$

where FL is the algal growth attenuation factor for light for the water column, K_L is the half-saturation coefficient for light (MJ/m^2-hr), $I_{phosyn,hr}$ is the photosynthetically-active solar radiation reaching the ground/water surface during a specific hour on a given day (MJ/m^2-hr), k_ℓ is the light extinction coefficient (m^{-1}), and *depth* is the depth of water in the channel (m). The photosynthetically-active solar radiation is calculated:

$$I_{phosyn,hr} = I_{hr} \cdot fr_{phosyn} \qquad\qquad 25.1.9$$

where I_{hr} is the solar radiation reaching the ground during a specific hour on current day of simulation (MJ m^{-2} h^{-1}), and fr_{phosyn} is the fraction of solar radiation that is photosynthetically active. The calculation of I_{hr} is reviewed in Chapter 2. The fraction of solar radiation that is photosynthetically active is user defined.

For daily simulations, an average value of the algal growth attenuation factor for light calculated over the diurnal cycle must

be used. This is calculated using a modified form of equation
25.1.8:

$$FL = 0.92 \cdot fr_{DL} \cdot \left(\frac{1}{k_\ell \cdot depth} \right) \cdot \ln\left[\frac{K_L + \bar{I}_{phosyn,hr}}{K_L + \bar{I}_{phosyn,hr} \exp\left(- k_\ell \cdot depth\right)} \right] \quad 25.1.10$$

where fr_{DL} is the fraction of daylight hours, $\bar{I}_{phosyn,hr}$ is the daylight
average photosynthetically-active light intensity (MJ/m^2-hr) and all
other variables are defined previously. The fraction of daylight
hours is calculated:

$$fr_{DL} = \frac{T_{DL}}{24} \quad 25.1.11$$

where T_{DL} is the daylength (hr). $\bar{I}_{phosyn,hr}$ is calculated:

$$\bar{I}_{phosyn,hr} = \frac{fr_{phosyn} \cdot H_{day}}{T_{DL}} \quad 25.1.12$$

where fr_{phosyn} is the fraction of solar radiation that is
photosynthetically active, H_{day} is the solar radiation reaching the
water surface in a given day (MJ/m^2), and T_{DL} is the daylength
(hr). Calculation of H_{day} and T_{DL} are reviewed in Chapter 2.

The light extinction coefficient, k_ℓ, is calculated as a
function of the algal density using the nonlinear equation:

$$k_\ell = k_{\ell,0} + k_{\ell,1} \cdot \alpha_0 \cdot algae + k_{\ell,2} \cdot \left(\alpha_0 \cdot algae\right)^{2/3} \quad 25.1.13$$

where $k_{\ell,0}$ is the non-algal portion of the light extinction
coefficient (m^{-1}), $k_{\ell,1}$ is the linear algal self shading coefficient (m^{-1} (μg-chla/L)$^{-1}$), $k_{\ell,2}$ is the nonlinear algal self shading coefficient
(m^{-1} (μg-chla/L)$^{-2/3}$), α_0 is the ratio of chlorophyll a to algal
biomass (μg chla/mg alg), and *algae* is the algal biomass
concentration (mg alg/L).

Equation 25.1.13 allows a variety of algal, self-shading, light
extinction relationships to be modeled. When $k_{\ell,1} = k_{\ell,2} = 0$, no

algal self-shading is simulated. When $k_{\ell,1} \neq 0$ and $k_{\ell,2} = 0$, linear algal self-shading is modeled. When $k_{\ell,1}$ and $k_{\ell,2}$ are set to a value other than 0, non-linear algal self-shading is modeled. The Riley equation (Bowie et al., 1985) defines $k_{\ell,1} = 0.0088 \text{ m}^{-1} \left(\mu g \text{ - chla/L}\right)^{-1}$ and $k_{\ell,2} = 0.054 \text{ m}^{-1} \left(\mu g \text{ - chla/L}\right)^{-2/3}$.

ALGAL GROWTH LIMITING FACTOR FOR NUTRIENTS.

The algal growth limiting factor for nitrogen is defined by a Monod expression. Algae are assumed to use both ammonia and nitrate as a source of inorganic nitrogen.

$$FN = \frac{\left(C_{NO3} + C_{NH4}\right)}{\left(C_{NO3} + C_{NH4}\right) + K_N} \qquad 25.1.14$$

where *FN* is the algal growth limitation factor for nitrogen, C_{NO3} is the concentration of nitrate in the reach (mg N/L), C_{NH4} is the concentration of ammonium in the reach (mg N/L), and K_N is the Michaelis-Menton half-saturation constant for nitrogen (mg N/L).

The algal growth limiting factor for phosphorus is also defined by a Monod expression.

$$FP = \frac{C_{solP}}{C_{solP} + K_P} \qquad 25.1.15$$

where *FP* is the algal growth limitation factor for phosphorus, C_{solP} is the concentration of phosphorus in solution in the reach (mg P/L), and K_P is the Michaelis-Menton half-saturation constant for phosphorus (mg P/L).

The Michaelis-Menton half-saturation constant for nitrogen and phosphorus define the concentration of N or P at which algal growth is limited to 50% of the maximum growth rate. Users are allowed to set these values. Typical values for K_N range from 0.01 to 0.30 mg N/L while K_P will range from 0.001 to 0.05 mg P/L.

Once the algal growth rate at 20°C is calculated, the rate coefficient is adjusted for temperature effects using a Streeter-Phelps type formulation:

$$\mu_a = \mu_{a,20} \cdot 1.047^{(T_{water}-20)}$$
25.1.16

where μ_a is the local specific growth rate of algae (day^{-1}), $\mu_{a,20}$ is the local specific algal growth rate at 20°C (day^{-1}), and T_{water} is the average water temperature for the day (°C).

25.1.2.2 LOCAL RESPIRATION RATE OF ALGAE

The local respiration or death rate of algae represents the net effect of three processes: the endogenous respiration of algae, the conversion of algal phosphorus to organic phosphorus, and the conversion of algal nitrogen to organic nitrogen. The user defines the local respiration rate of algae at 20°C. The respiration rate is adjusted to the local water temperature using the relationship:

$$\rho_a = \rho_{a,20} \cdot 1.047^{(T_{water}-20)}$$
25.1.17

where ρ_a is the local respiration rate of algae (day^{-1}), $\rho_{a,20}$ is the local algal respiration rate at 20°C (day^{-1}), and T_{water} is the average water temperature for the day (°C).

25.1.2.3 LOCAL SETTLING RATE OF ALGAE

The local settling rate of algae represents the net removal of algae due to settling. The user defines the local settling rate of algae at 20°C. The settling rate is adjusted to the local water temperature using the relationship:

$$\sigma_1 = \sigma_{1,20} \cdot 1.024^{(T_{water}-20)}$$
25.1.18

where σ_1 is the local settling rate of algae (m/day), $\sigma_{1,20}$ is the local algal settling rate at 20°C (m/day), and T_{water} is the average water temperature for the day (°C).

Table 25-1: SWAT input variables used in algae calculations.

Variable name	Definition	File Name
AI0	α_0: Ratio of chlorophyll *a* to algal biomass (µg chla/mg alg)	.wwq
MUMAX	μ_{max}: Maximum specific algal growth rate (day^{-1})	.wwq
K_L	K_L: Half-saturation coefficient for light (MJ/m^2-hr)	.wwq
TFACT	fr_{phosyn}: Fraction of solar radiation that is photosynthetically active	.wwq
LAMBDA0	$k_{\ell,0}$: Non-algal portion of the light extinction coefficient (m^{-1})	.wwq
LAMBDA1	$k_{\ell,1}$: Linear algal self shading coefficient (m^{-1} (µg-chla/L)$^{-1}$)	.wwq
LAMBDA2	$k_{\ell,2}$: Nonlinear algal self shading coefficient (m^{-1} (µg-chla/L)$^{-2/3}$)	.wwq
K_N	K_N: Michaelis-Menton half-saturation constant for nitrogen (mg N/L)	.wwq
K_P	K_P: Michaelis-Menton half-saturation constant for phosphorus (mg P/L)	.wwq
RHOQ	$\rho_{a,20}$: Local algal respiration rate at 20°C (day^{-1})	.wwq
RS1	$\sigma_{1,20}$: Local algal settling rate at 20°C (m/day)	.swq

25.2 NITROGEN CYCLE

In aerobic water, there is a stepwise transformation from organic nitrogen to ammonia, to nitrite, and finally to nitrate. Organic nitrogen may also be removed from the stream by settling. This section summarizes the equations used to simulate the nitrogen cycle in the stream.

25.2.1 ORGANIC NITROGEN

The amount of organic nitrogen in the stream may be increased by the conversion of algal biomass nitrogen to organic nitrogen. Organic nitrogen concentration in the stream may be decreased by the conversion of organic nitrogen to NH_4^+ or the settling of organic nitrogen with sediment. The change in organic nitrogen for a given day is:

$$\Delta orgN_{str} = \left(\alpha_1 \cdot \rho_a \cdot algae - \beta_{N,3} \cdot orgN_{str} - \sigma_4 \cdot orgN_{str} \right) \cdot TT \qquad 25.2.1$$

where $\Delta orgN_{str}$ is the change in organic nitrogen concentration (mg N/L), α_1 is the fraction of algal biomass that is nitrogen (mg N/mg alg biomass), ρ_a is the local respiration or death rate of algae (day^{-1}), *algae* is the algal biomass concentration at the beginning of the day (mg alg/L), $\beta_{N,3}$ is the rate constant for hydrolysis of organic nitrogen to ammonia nitrogen (day^{-1}), $orgN_{str}$ is the organic nitrogen concentration at the beginning of the day (mg N/L), σ_4 is the rate coefficient for organic nitrogen settling (day^{-1}), and *TT* is the flow travel time in the reach

segment (day). The fraction of algal biomass that is nitrogen is user-defined. Equation 25.1.17 describes the calculation of the local respiration rate of algae. The calculation of travel time is reviewed in Chapter 23.

The user defines the local rate constant for hydrolysis of organic nitrogen to NH_4^+ at 20°C. The organic nitrogen hydrolysis rate is adjusted to the local water temperature using the relationship:

$$\beta_{N,3} = \beta_{N,3,20} \cdot 1.047^{(T_{water}-20)}$$ 25.2.2

where $\beta_{N,3}$ is the local rate constant for hydrolysis of organic nitrogen to NH_4^+ (day^{-1}), $\beta_{N,3,20}$ is the local rate constant for hydrolysis of organic nitrogen to NH_4^+ at 20°C (day^{-1}), and T_{water} is the average water temperature for the day (°C).

The user defines the rate coefficient for organic nitrogen settling at 20°C. The organic nitrogen settling rate is adjusted to the local water temperature using the relationship:

$$\sigma_4 = \sigma_{4,20} \cdot 1.024^{(T_{water}-20)}$$ 25.2.3

where σ_4 is the local settling rate for organic nitrogen (day^{-1}), $\sigma_{4,20}$ is the local settling rate for organic nitrogen at 20°C (day^{-1}), and T_{water} is the average water temperature for the day (°C).

25.2.2 AMMONIUM

The amount of ammonium (NH_4^+) in the stream may be increased by the mineralization of organic nitrogen and diffusion of ammonium from the streambed sediments. The ammonium concentration in the stream may be decreased by the conversion of NH_4^+ to NO_2^- or the uptake of NH_4^+ by algae. The change in ammonium for a given day is:

$$\Delta NH4_{str} = \left(\beta_{N,3} \cdot orgN_{str} - \beta_{N,1} \cdot NH4_{str} + \frac{\sigma_3}{(1000 \cdot depth)} - fr_{NH4} \cdot \alpha_1 \cdot \mu_a \cdot algae \right) \cdot TT$$ 25.2.4

where $\Delta NH4_{str}$ is the change in ammonium concentration (mg N/L), $\beta_{N,3}$ is the rate constant for hydrolysis of organic nitrogen to ammonia nitrogen (day^{-1}), $orgN_{str}$ is the organic nitrogen concentration at the beginning of the day (mg N/L), $\beta_{N,1}$ is the rate constant for biological oxidation of ammonia nitrogen (day^{-1}),

$NH4_{str}$ is the ammonium concentration at the beginning of the day (mg N/L), σ_3 is the benthos (sediment) source rate for ammonium (mg N/m^2-day), *depth* is the depth of water in the channel (m), fr_{NH4} is the fraction of algal nitrogen uptake from ammonium pool, α_1 is the fraction of algal biomass that is nitrogen (mg N/mg alg biomass), μ_a is the local growth rate of algae (day^{-1}), *algae* is the algal biomass concentration at the beginning of the day (mg alg/L), and *TT* is the flow travel time in the reach segment (day). The local rate constant for hydrolysis of organic nitrogen to NH_4^+ is calculated with equation 25.2.2. Section 25.1.2.1 describes the calculation of the local growth rate of algae. The calculation of depth and travel time is reviewed in Chapter 23.

The rate constant for biological oxidation of ammonia nitrogen will vary as a function of in-stream oxygen concentration and temperature. The rate constant is calculated:

$$\beta_{N,1} = \beta_{N,1,20} \cdot \left(1 - \exp\left[-0.6 \cdot Ox_{str}\right]\right) \cdot 1.083^{(T_{water}-20)}$$ 25.2.5

where $\beta_{N,1}$ is the rate constant for biological oxidation of ammonia nitrogen (day^{-1}), $\beta_{N,1,20}$ is the rate constant for biological oxidation of ammonia nitrogen at 20°C (day^{-1}), Ox_{str} is the dissolved oxygen concentration in the stream (mg O$_2$/L), and T_{water} is the average water temperature for the day (°C). The second term on the right side of equation 25.2.5, $\left(1 - \exp\left[-0.6 \cdot Ox_{str}\right]\right)$, is a nitrification inhibition correction factor. This factor inhibits nitrification at low dissolved oxygen concentrations.

The user defines the benthos source rate for ammonium at 20°C. The benthos source rate for ammonium nitrogen is adjusted to the local water temperature using the relationship:

$$\sigma_3 = \sigma_{3,20} \cdot 1.074^{(T_{water}-20)}$$ 25.2.6

where σ_3 is the benthos (sediment) source rate for ammonium (mg N/m^2-day), $\sigma_{3,20}$ is the benthos (sediment) source rate for ammonium nitrogen at 20°C (mg N/m^2-day), and T_{water} is the average water temperature for the day (°C).

The fraction of algal nitrogen uptake from ammonium pool is calculated:

$$fr_{NH4} = \frac{f_{NH4} \cdot NH4_{str}}{\left(f_{NH4} \cdot NH4_{str} + \left(1 - f_{NH4}\right) \cdot NO3_{str}\right)} \qquad \text{25.2.7}$$

where fr_{NH4} is the fraction of algal nitrogen uptake from ammonium pool, f_{NH4} is the preference factor for ammonia nitrogen, $NH4_{str}$ is the ammonium concentration in the stream (mg N/L), and $NO3_{str}$ is the nitrate concentration in the stream (mg N/L).

25.2.3 NITRITE

The amount of nitrite (NO_2^-) in the stream will be increased by the conversion of NH_4^+ to NO_2^- and decreased by the conversion of NO_2^- to NO_3^-. The conversion of NO_2^- to NO_3^- occurs more rapidly than the conversion of NH_4^+ to NO_2^-, so the amount of nitrite present in the stream is usually very small. The change in nitrite for a given day is:

$$\Delta NO2_{str} = \left(\beta_{N,1} \cdot NH4_{str} - \beta_{N,2} \cdot NO2_{str}\right) \cdot TT \qquad \text{25.2.8}$$

where $\Delta NO2_{str}$ is the change in nitrite concentration (mg N/L), $\beta_{N,1}$ is the rate constant for biological oxidation of ammonia nitrogen (day^{-1}), $NH4_{str}$ is the ammonium concentration at the beginning of the day (mg N/L), $\beta_{N,2}$ is the rate constant for biological oxidation of nitrite to nitrate (day^{-1}), $NO2_{str}$ is the nitrite concentration at the beginning of the day (mg N/L), and TT is the flow travel time in the reach segment (day). The local rate constant for biological oxidation of ammonia nitrogen is calculated with equation 25.2.5. The calculation of travel time is reviewed in Chapter 23.

The rate constant for biological oxidation of nitrite to nitrate will vary as a function of in-stream oxygen concentration and temperature. The rate constant is calculated:

$$\beta_{N,2} = \beta_{N,2,20} \cdot \left(1 - \exp\left[-0.6 \cdot Ox_{str}\right]\right) \cdot 1.047^{(T_{water} - 20)} \qquad \text{25.2.9}$$

where $\beta_{N,2}$ is the rate constant for biological oxidation of nitrite to nitrate (day^{-1}), $\beta_{N,2,20}$ is the rate constant for biological oxidation of nitrite to nitrate at 20°C (day^{-1}), Ox_{str} is the dissolved oxygen concentration in the stream (mg O$_2$/L), and T_{water} is the average water temperature for the day (°C). The second term on the

right side of equation 25.2.9, $(1 - \exp[-0.6 \cdot Ox_{str}])$, is a nitrification inhibition correction factor. This factor inhibits nitrification at low dissolved oxygen concentrations.

25.2.4 NITRATE

The amount of nitrate (NO_3^-) in the stream may be increased by the oxidation of NO_2^-. The nitrate concentration in the stream may be decreased by the uptake of NO_3^- by algae. The change in nitrate for a given day is:

$$\Delta NO3_{str} = \left(\beta_{N,2} \cdot NO2_{str} - (1 - fr_{NH4}) \cdot \alpha_1 \cdot \mu_a \cdot algae\right) \cdot TT \qquad 25.2.10$$

where $\Delta NO3_{str}$ is the change in nitrate concentration (mg N/L), $\beta_{N,2}$ is the rate constant for biological oxidation of nitrite to nitrate (day^{-1}), $NO2_{str}$ is the nitrite concentration at the beginning of the day (mg N/L), fr_{NH4} is the fraction of algal nitrogen uptake from ammonium pool, α_1 is the fraction of algal biomass that is nitrogen (mg N/mg alg biomass), μ_a is the local growth rate of algae (day^{-1}), $algae$ is the algal biomass concentration at the beginning of the day (mg alg/L), and TT is the flow travel time in the reach segment (day). The local rate constant for biological oxidation of nitrite to nitrate is calculated with equation 25.2.9 while the fraction of algal nitrogen uptake from ammonium pool is calculated with equation 25.2.7. Section 25.1.2.1 describes the calculation of the local growth rate of algae. The calculation of travel time is reviewed in Chapter 23.

Table 25-2: SWAT input variables used in-stream nitrogen calculations.

Variable name	Definition	File Name
AI1	α_1: Fraction of algal biomass that is nitrogen (mg N/mg alg biomass)	.wwq
RHOQ	$\rho_{a,20}$: Local algal respiration rate at 20°C (day^{-1})	.wwq
BC3	$\beta_{N,3,20}$: Local rate constant for hydrolysis of organic nitrogen to NH_4^+ at 20°C (day^{-1} or hr^{-1})	.swq
RS4	$\sigma_{4,20}$: Local settling rate for organic nitrogen at 20°C (day^{-1})	.swq
BC1	$\beta_{N,1,20}$: Rate constant for biological oxidation of ammonia nitrogen at 20°C (day^{-1})	.swq
RS3	$\sigma_{3,20}$: Benthos (sediment) source rate for ammonium nitrogen at 20°C (mg N/m^2-day or mg N/m^2-hr)	.swq
P_N	f_{NH4}: Preference factor for ammonia nitrogen	.wwq
BC2	$\beta_{N,2,20}$: Rate constant for biological oxidation of nitrite to nitrate at 20°C (day^{-1} or hr^{-1})	.swq

25.3 PHOSPHORUS CYCLE

The phosphorus cycle is similar to the nitrogen cycle. The death of algae transforms algal phosphorus into organic phosphorus. Organic phosphorus is mineralized to soluble phosphorus which is available for uptake by algae. Organic phosphorus may also be removed from the stream by settling. This section summarizes the equations used to simulate the phosphorus cycle in the stream.

25.3.1 ORGANIC PHOSPHORUS

The amount of organic phosphorus in the stream may be increased by the conversion of algal biomass phosphorus to organic phosphorus. Organic phosphorus concentration in the stream may be decreased by the conversion of organic phosphorus to soluble inorganic phosphorus or the settling of organic phosphorus with sediment. The change in organic phosphorus for a given day is:

$$\Delta orgP_{str} = \left(\alpha_2 \cdot \rho_a \cdot algae - \beta_{P,4} \cdot orgP_{str} - \sigma_5 \cdot orgP_{str} \right) \cdot TT \qquad 25.3.1$$

where $\Delta orgP_{str}$ is the change in organic phosphorus concentration (mg P/L), α_2 is the fraction of algal biomass that is phosphorus (mg P/mg alg biomass), ρ_a is the local respiration or death rate of algae (day^{-1}), $algae$ is the algal biomass concentration at the beginning of the day (mg alg/L), $\beta_{P,4}$ is the rate constant for mineralization of organic phosphorus (day^{-1}), $orgP_{str}$ is the organic phosphorus concentration at the beginning of the day (mg P/L), σ_5 is the rate coefficient for organic phosphorus settling (day^{-1}), and TT is the flow travel time in the reach segment (day). The fraction of algal biomass that is phosphorus is user-defined. Equation 25.1.17 describes the calculation of the local respiration rate of algae. The calculation of travel time is reviewed in Chapter 23.

The user defines the local rate constant for mineralization of organic phosphorus at 20°C. The organic phosphorus mineralization rate is adjusted to the local water temperature using the relationship:

$$\beta_{P,4} = \beta_{P,4,20} \cdot 1.047^{(T_{water}-20)} \qquad 25.3.2$$

where $\beta_{P,4}$ is the local rate constant for organic phosphorus mineralization (day^{-1}), $\beta_{P,4,20}$ is the local rate constant for organic phosphorus mineralization at 20°C (day^{-1}), and T_{water} is the average water temperature for the day (°C).

The user defines the rate coefficient for organic phosphorus settling at 20°C. The organic phosphorus settling rate is adjusted to the local water temperature using the relationship:

$$\sigma_5 = \sigma_{5,20} \cdot 1.024^{(T_{water}-20)}$$ 25.3.3

where σ_5 is the local settling rate for organic phosphorus (day^{-1}), $\sigma_{5,20}$ is the local settling rate for organic phosphorus at 20°C (day^{-1}), and T_{water} is the average water temperature for the day (°C).

25.3.2 INORGANIC/SOLUBLE PHOSPHORUS

The amount of soluble, inorganic phosphorus in the stream may be increased by the mineralization of organic phosphorus and diffusion of inorganic phosphorus from the streambed sediments. The soluble phosphorus concentration in the stream may be decreased by the uptake of inorganic P by algae. The change in soluble phosphorus for a given day is:

$$\Delta solP_{str} = \left(\beta_{P,4} \cdot orgP_{str} + \frac{\sigma_2}{(1000 \cdot depth)} - \alpha_2 \cdot \mu_a \cdot algae \right) \cdot TT$$ 25.3.4

where $\Delta solP_{str}$ is the change in solution phosphorus concentration (mg P/L), $\beta_{P,4}$ is the rate constant for mineralization of organic phosphorus (day^{-1}), $orgP_{str}$ is the organic phosphorus concentration at the beginning of the day (mg P/L), σ_2 is the benthos (sediment) source rate for soluble P (mg P/m^2-day), $depth$ is the depth of water in the channel (m), α_2 is the fraction of algal biomass that is phosphorus (mg P/mg alg biomass), μ_a is the local growth rate of algae (day^{-1}), $algae$ is the algal biomass concentration at the beginning of the day (mg alg/L), and TT is the flow travel time in the reach segment (day). The local rate constant for mineralization of organic phosphorus is calculated with equation 25.3.2. Section 25.1.2.1 describes the calculation of the local growth rate of algae. The calculation of depth and travel time is reviewed in Chapter 23.

The user defines the benthos source rate for soluble P at 20°C. The benthos source rate for soluble phosphorus is adjusted to the local water temperature using the relationship:

$$\sigma_2 = \sigma_{2,20} \cdot 1.074^{(T_{water}-20)}$$ 25.3.5

where σ_2 is the benthos (sediment) source rate for soluble P (mg P/m²-day), $\sigma_{2,20}$ is the benthos (sediment) source rate for soluble phosphorus at 20°C (mg P/m²-day), and T_{water} is the average water temperature for the day (°C).

Table 25-3: SWAT input variables used in in-stream phosphorus calculations.

Variable name	Definition	File Name
AI2	α_2: Fraction of algal biomass that is phosphorus (mg P/mg alg biomass)	.wwq
RHOQ	$\rho_{a,20}$: Local algal respiration rate at 20°C (day⁻¹)	.wwq
BC4	$\beta_{P,4,20}$: Local rate constant for organic phosphorus mineralization at 20°C (day⁻¹)	.swq
RS5	$\sigma_{5,20}$: Local settling rate for organic phosphorus at 20°C (day⁻¹)	.swq
RS2	$\sigma_{2,20}$: Benthos (sediment) source rate for soluble phosphorus at 20°C (mg P/m²-day)	.swq

25.4 CARBONACEOUS BIOLOGICAL OXYGEN DEMAND

The carbonaceous oxygen demand (CBOD) of the water is the amount of oxygen required to decompose the organic material in the water. CBOD is added to the stream with loadings from surface runoff or point sources. Within the stream, two processes are modeled that impact CBOD levels, both of which serve to reduce the carbonaceous biological oxygen demand as the water moves downstream. The change in CBOD within the stream on a given day is calculated:

$$\Delta cbod = -(\kappa_1 \cdot cbod + \kappa_3 \cdot cbod) \cdot TT$$ 25.4.1

where $\Delta cbod$ is the change in carbonaceous biological oxygen demand concentration (mg CBOD/L), κ_1 is the CBOD deoxygenation rate (day⁻¹), $cbod$ is the carbonaceous biological oxygen demand concentration (mg CBOD/L), κ_3 is the settling loss rate of CBOD (day⁻¹), and TT is the flow travel time in the reach segment (day). The calculation of travel time is reviewed in Chapter 23.

The user defines the carbonaceous deoxygenation rate at 20°C. The CBOD deoxygenation rate is adjusted to the local water temperature using the relationship:

$$\kappa_1 = \kappa_{1,20} \cdot 1.047^{(T_{water}-20)}$$ 25.4.2

where κ_1 is the CBOD deoxygenation rate (day^{-1}), $\kappa_{1,20}$ is the CBOD deoxygenation rate at 20°C (day^{-1}), and T_{water} is the average water temperature for the day (°C).

The user defines the settling loss rate of CBOD at 20°C. The settling loss rate is adjusted to the local water temperature using the relationship:

$$\kappa_3 = \kappa_{3,20} \cdot 1.024^{(T_{water}-20)}$$ 25.4.3

where κ_3 is the settling loss rate of CBOD (day^{-1}), $\kappa_{3,20}$ is the settling loss rate of CBOD at 20°C (day^{-1}), and T_{water} is the average water temperature for the day (°C).

Table 25-4: SWAT input variables used in in-stream CBOD calculations.

Variable name	Definition	File Name
RK1	$\kappa_{1,20}$: CBOD deoxygenation rate at 20°C (day^{-1})	.swq
RK3	$\kappa_{3,20}$: Settling loss rate of CBOD at 20°C (day^{-1})	.swq

25.5 OXYGEN

An adequate dissolved oxygen concentration is a basic requirement for a healthy aquatic ecosystem. Dissolved oxygen concentrations in streams are a function of atmospheric reareation, photosynthesis, plant and animal respiration, benthic (sediment) demand, biochemical oxygen demand, nitrification, salinity, and temperature. The change in dissolved oxygen concentration on a given day is calculated:

$$\Delta Ox_{str} = (\kappa_2 \cdot (Ox_{sat} - Ox_{str}) + (\alpha_3 \cdot \mu_a - \alpha_4 \cdot \rho_a) \cdot algae - \kappa_1 \cdot cbod - \frac{\kappa_4}{1000 \cdot depth}$$

$$- \alpha_5 \cdot \beta_{N,1} \cdot NH4_{str} - \alpha_6 \cdot \beta_{N,2} \cdot NO2_{str}) \cdot TT$$ 25.5.1

where ΔOx_{str} is the change in dissolved oxygen concentration (mg O$_2$/L), κ_2 is the reaeration rate for Fickian diffusion (day^{-1}), Ox_{sat} is the saturation oxygen

concentration (mg O_2/L), Ox_{str} is the dissolved oxygen concentration in the stream (mg O_2/L), α_3 is the rate of oxygen production per unit of algal photosynthesis (mg O_2/mg alg), μ_a is the local specific growth rate of algae (day^{-1}), α_4 is the rate of oxygen uptake per unit of algae respired (mg O_2/mg alg), ρ_a is the local respiration or death rate of algae (day^{-1}), *algae* is the algal biomass concentration at the beginning of the day (mg alg/L), κ_1 is the CBOD deoxygenation rate (day^{-1}), *cbod* is the carbonaceous biological oxygen demand concentration (mg CBOD/L), κ_4 is the sediment oxygen demand rate (mg O_2/(m^2·day)), *depth* is the depth of water in the channel (m), α_5 is the rate of oxygen uptake per unit NH_4^+ oxidation (mg O_2/mg N), $\beta_{N,1}$ is the rate constant for biological oxidation of ammonia nitrogen (day^{-1}), *NH4$_{str}$* is the ammonium concentration at the beginning of the day (mg N/L), α_6 is the rate of oxygen uptake per unit NO_2^- oxidation (mg O_2/mg N), $\beta_{N,2}$ is the rate constant for biological oxidation of nitrite to nitrate (day^{-1}), *NO2$_{str}$* is the nitrite concentration at the beginning of the day (mg N/L) and *TT* is the flow travel time in the reach segment (day). The user defines the rate of oxygen production per unit algal photosynthesis, the rate of oxygen uptake per unit algal respiration, the rate of oxygen uptake per unit NH_4^+ oxidation and rate of oxygen uptake per unit NO_2^- oxidation. Section 25.1.2.1 describes the calculation of the local growth rate of algae while equation 25.1.17 describes the calculation of the local respiration rate of algae. The rate constant for biological oxidation of NH_4^+ is calculated with equation 25.2.5 while the rate constant for NO_2^- oxidation is determined with equation 25.2.9. The CBOD deoxygenation rate is calculated using equation 25.4.2. The calculation of depth and travel time are reviewed in Chapter 23.

The user defines the sediment oxygen demand rate at 20°C. The sediment oxygen demand rate is adjusted to the local water temperature using the relationship:

$$\kappa_4 = \kappa_{4,20} \cdot 1.060^{(T_{water}-20)} \qquad\qquad 25.5.2$$

where κ_4 is the sediment oxygen demand rate (mg $O_2/(m^2 \cdot day)$), $\kappa_{4,20}$ is the sediment oxygen demand rate at 20°C (mg $O_2/(m^2 \cdot day)$), and T_{water} is the average water temperature for the day (°C).

25.5.1 OXYGEN SATURATION CONCENTRATION

The amount of oxygen that can be dissolved in water is a function of temperature, concentration of dissolved solids, and atmospheric pressure. An equation developed by APHA (1985) is used to calculate the saturation concentration of dissolved oxygen:

$$Ox_{sat} = \exp\left[-139.34410 + \frac{1.575701 \times 10^5}{T_{wat,K}} - \frac{6.642308 \times 10^7}{T_{wat,K}^2} \right.$$
$$\left. + \frac{1.243800 \times 10^{10}}{T_{wat,K}^3} - \frac{8.621949 \times 10^{11}}{T_{wat,K}^4} \right] \qquad 25.5.3$$

where Ox_{sat} is the equilibrium saturation oxygen concentration at 1.00 atm (mg O_2/L), and $T_{wat,K}$ is the water temperature in Kelvin (273.15+°C).

25.5.2 REAERATION

Reaeration occurs by diffusion of oxygen from the atmosphere into the stream and by the mixing of water and air that occurs during turbulent flow.

25.5.2.1 REAERATION BY FICKIAN DIFFUSION

The user defines the reaeration rate at 20°C. The reaeration rate is adjusted to the local water temperature using the relationship:

$$\kappa_2 = \kappa_{2,20} \cdot 1.024^{(T_{water} - 20)} \qquad\qquad 25.5.4$$

where κ_2 is the reaeration rate (day^{-1}), $\kappa_{2,20}$ is the reaeration rate at 20°C (day^{-1}), and T_{water} is the average water temperature for the day (°C).

Numerous methods have been developed to calculate the reaeration rate at 20°C, $\kappa_{2,20}$. A few of the methods are listed below. Brown and Barnwell (1987) provide additional methods.

Using field measurements, Churchill, Elmore and Buckingham (1962) derived the relationship:

$$\kappa_{2,20} = 5.03 \cdot v_c^{0.969} \cdot depth^{-1.673} \qquad\qquad 25.5.5$$

where $\kappa_{2,20}$ is the reaeration rate at 20°C (day^{-1}), v_c is the average stream velocity (m/s), and *depth* is the average stream depth (m).

O'Connor and Dobbins (1958) incorporated stream turbulence characteristics into the equations they developed. For streams with low velocities and isotropic conditions,

$$\kappa_{2,20} = 294 \cdot \frac{\left(D_m \cdot v_c\right)^{0.5}}{depth^{1.5}}$$
25.5.6

where $\kappa_{2,20}$ is the reaeration rate at 20°C (day^{-1}), D_m is the molecular diffusion coefficient (m^2/day), v_c is the average stream velocity (m/s), and *depth* is the average stream depth (m). For streams with high velocities and nonisotropic conditions,

$$\kappa_{2,20} = 2703 \cdot \frac{D_m^{0.5} \cdot slp^{0.25}}{depth^{1.25}}$$
25.5.7

where $\kappa_{2,20}$ is the reaeration rate at 20°C (day^{-1}), D_m is the molecular diffusion coefficient (m^2/day), *slp* is the slope of the streambed (m/m), and *depth* is the average stream depth (m). The molecular diffusion coefficient is calculated

$$D_m = 177 \cdot 1.037^{\overline{T}_{water}-20}$$
25.5.8

where D_m is the molecular diffusion coefficient (m^2/day), and $\overline{T}_{water}$ is the average water temperature (°C).

Owens et al. (1964) developed an equation to determine the reaeration rate for shallow, fast moving streams where the stream depth is 0.1 to 3.4 m and the velocity is 0.03 to 1.5 m/s.

$$\kappa_{2,20} = 5.34 \cdot \frac{v_c^{0.67}}{depth^{1.85}}$$
25.5.9

where $\kappa_{2,20}$ is the reaeration rate at 20°C (day^{-1}), v_c is the average stream velocity (m/s), and *depth* is the average stream depth (m).

25.5.2.2 REAERATION BY TURBULENT FLOW OVER A DAM

Reareation will occur when water falls over a dam, weir, or other structure in the stream. To simulate this form of reaeration, a "structure" command line is added in the watershed configuration file (.fig) at every point along the stream where flow over a structure occurs.

The amount of reaeration that occurs is a function of the oxygen deficit above the structure and a reaeration coefficient:

$$\Delta Ox_{str} = D_a - D_b = D_a\left(1 - \frac{1}{rea}\right) \qquad 25.5.10$$

where ΔOx_{str} is the change in dissolved oxygen concentration (mg O_2/L), D_a is the oxygen deficit above the structure (mg O_2/L), D_b is the oxygen deficit below the structure (mg O_2/L), and rea is the reaeration coefficient.

The oxygen deficit above the structure, D_a, is calculated:

$$D_a = Ox_{sat} - Ox_{str} \qquad 25.5.11$$

where Ox_{sat} is the equilibrium saturation oxygen concentration (mg O_2/L), and Ox_{str} is the dissolved oxygen concentration in the stream (mg O_2/L).

Butts and Evans (1983) documents the following relationship that can be used to estimate the reaeration coefficient:

$$rea = 1 + 0.38 \cdot coef_a \cdot coef_b \cdot h_{fall} \cdot \left(1 - 0.11 \cdot h_{fall}\right) \cdot \left(1 + 0.046 \cdot \overline{T}_{water}\right) \quad 25.5.12$$

where rea is the reaeration coefficient, $coef_a$ is an empirical water quality factor, $coef_b$ is an empirical dam aeration coefficient, h_{fall} is the height through which water falls (m), and $\overline{T}_{water}$ is the average water temperature (°C).

The empirical water quality factor is assigned a value based on the condition of the stream:

$coef_a = 1.80$ in clean water

$coef_a = 1.60$ in slightly polluted water

$coef_a = 1.00$ in moderately polluted water

$coef_a = 1.00$ in moderately polluted water

$coef_a = 0.65$ in grossly polluted water

The empirical dam aeration coefficient is assigned a value based on the type of structure:

$coef_b$ = 0.70 to 0.90 for flat broad crested weir

$coef_b$ = 1.05 for sharp crested weir with straight slope face

$coef_b$ = 0.80 for sharp crested weir with vertical face

$coef_b$ = 0.05 for sluice gates with submerged discharge

Table 25-5: SWAT input variables used in in-stream oxygen calculations.

Variable name	Definition	File Name
RK2	$\kappa_{2,20}$: Reaeration rate at 20°C (day^{-1})	.swq
AI3	α_3: Rate of oxygen production per unit algal photosynthesis (mg O$_2$/mg alg)	.wwq
AI4	α_4: Rate of oxygen uptake per unit algal respiration (mg O$_2$/mg alg)	.wwq
RHOQ	$\rho_{a,20}$: Local algal respiration rate at 20°C (day^{-1})	.wwq
RK1	$\kappa_{1,20}$: CBOD deoxygenation rate at 20°C (day^{-1})	.swq
RK4	$\kappa_{4,20}$: Sediment oxygen demand rate at 20°C (mg O$_2$/(m^2·day))	.swq
AI5	α_5: Rate of oxygen uptake per unit NH$_4^+$ oxidation (mg O$_2$/mg N)	.wwq
AI6	α_6: Rate of oxygen uptake per unit NO$_2$ oxidation (mg O$_2$/mg N)	.wwq
AERATION_COEF	rea: Reaeration coefficient	.fig

25.6 NOMENCLATURE

C_{NH4} Concentration of ammonium in the reach (mg N/L)

C_{NO3} Concentration of nitrate in the reach (mg N/L)

C_{solP} Concentration of phosphorus in solution in the reach (mg P/L)

D_a Oxygen deficit above the structure (mg O$_2$/L)

D_b Oxygen deficit below the structure (mg O$_2$/L)

D_m Molecular diffusion coefficient for oxygen (m^2/day)

FL Algal growth attenuation factor for light for the water column

FL_z Algal growth attenuation factor for light at depth z

FN Algal growth limitation factor for nitrogen

FP Algal growth limitation factor for phosphorus

H_{day} Solar radiation reaching ground on current day of simulation (MJ m^{-2} d^{-1})

I_{hr} Solar radiation reaching ground during specific hour on current day of simulation (MJ m^{-2} h^{-1})

$I_{phosyn,hr}$Photosynthetically-active solar radiation reaching ground during specific hour on current day of simulation (MJ m^{-2} h^{-1})

$I_{phosyn,z}$ Photosynthetically-active light intensity at a depth z below the water surface (MJ/m^2-hr)

$\bar{I}_{phosyn,hr}$ Daylight average photosynthetically-active light intensity (MJ/m^2-hr)

K_L Half-saturation coefficient for light (MJ/m^2-hr)

K_N Michaelis-Menton half-saturation constant for nitrogen (mg N/L)

K_P Michaelis-Menton half-saturation constant for phosphorus (mg P/L)

$NH4_{str}$ Ammonium concentration in the stream (mg N/L)

$NO2_{str}$ Nitrite concentration in the stream (mg N/L)

$NO3_{str}$ Nitrate concentration in the stream (mg N/L)

Ox_{sat} Saturation oxygen concentration (mg O_2/L)

Ox_{str} Dissolved oxygen concentration in the stream (mg O_2/L)

T_{DL} Daylength (h)

T_{water} Average daily water temperature (°C)

$T_{wat,K}$ Water temperature in Kelvin (273.15+°C)

$\overline{T}_{water}$ Average water temperature (°C)

TT Travel time (day)

algae Algal biomass concentration (mg alg/L)

cbod   Carbonaceous biological oxygen demand concentration (mg CBOD/L)

chla   Chlorophyll *a* concentration (µg chla/L)

$coef_a$ Empirical water quality factor

$coef_b$ Empirical dam aeration coefficient

depth Depth of water in the channel (m)

f_{NH4} Preference factor for ammonia nitrogen

fr_{DL} Fraction of daylight hours

fr_{NH4} Fraction of algal nitrogen uptake from ammonium pool,

fr_{phosyn} Fraction of solar radiation that is photosynthetically active

h_{fall} Height through which water falls (m)

k_ℓ Light extinction coefficient (m^{-1})

$k_{\ell,0}$ Non-algal portion of the light extinction coefficient (m^{-1})

$k_{\ell,1}$ Linear algal self shading coefficient (m^{-1} (µg-chla/L)$^{-1}$)

$k_{\ell,2}$ Nonlinear algal self shading coefficient (m^{-1} (µg-chla/L)$^{-2/3}$)

$orgN_{str}$ Organic nitrogen concentration in the stream (mg N/L)

$orgP_{str}$ Organic phosphorus concentration in the stream (mg P/L)

rea   Reaeration coefficient

slp   Slope of the streambed (m/m)

v_c Average stream velocity (m/s)

z Depth from the water surface (m)

α_0 Ratio of chlorophyll *a* to algal biomass (µg chla/mg alg)

α_1 Fraction of algal biomass that is nitrogen (mg N/mg alg biomass),

α_2 Fraction of algal biomass that is phosphorus (mg P/mg alg biomass)

α_3 Rate of oxygen production per unit algal photosynthesis (mg O_2/mg alg)

α_4 Rate of oxygen uptake per unit algal respiration (mg O_2/mg alg)

α_5 Rate of oxygen uptake per unit NH_4^+ oxidation (mg O_2/mg N)

α_6 Rate of oxygen uptake per unit NO_2 oxidation (mg O_2/mg N)

$\beta_{N,1}$ Rate constant for biological oxidation of ammonia nitrogen (day^{-1} or hr^{-1})

$\beta_{N,1,20}$ Rate constant for biological oxidation of ammonia nitrogen at 20°C (day^{-1} or hr^{-1})

$\beta_{N,2}$ Rate constant for biological oxidation of nitrite to nitrate (day^{-1} or hr^{-1})

$\beta_{N,2,20}$ Rate constant for biological oxidation of nitrite to nitrate at 20°C (day^{-1} or hr^{-1})

$\beta_{N,3}$ Rate constant for hydrolysis of organic nitrogen to ammonia nitrogen (day^{-1} or hr^{-1})

$\beta_{N,3,20}$ Local rate constant for hydrolysis of organic nitrogen to NH$_4^+$ at 20°C (day^{-1} or hr^{-1})

$\beta_{P,4}$ Rate constant for mineralization of organic phosphorus (day^{-1} or hr^{-1})

$\beta_{P,4,20}$ Local rate constant for organic phosphorus mineralization at 20°C (day^{-1} or hr^{-1})

$\Delta algae$ Change in algal biomass concentration (mg alg/L)

$\Delta NH4_{str}$ Change in ammonium concentration (mg N/L)

$\Delta NO2_{str}$ Change in nitrite concentration (mg N/L)

$\Delta orgN_{str}$ Change in organic nitrogen concentration (mg N/L)

$\Delta orgP_{str}$ Change in organic phosphorus concentration (mg P/L)

ΔOx_{str} Change in dissolved oxygen concentration (mg O$_2$/L)

$\Delta solP_{str}$ Change in solution phosphorus concentration (mg P/L)

κ_1 CBOD deoxygenation rate (day^{-1} or hr^{-1})

$\kappa_{1,20}$ CBOD deoxygenation rate at 20°C (day^{-1} or hr^{-1})

κ_2 Reaeration rate for Fickian diffusion (day^{-1} or hr^{-1})

$\kappa_{2,20}$ Reaeration rate at 20°C (day^{-1} or hr^{-1})

κ_3 Settling loss rate of CBOD (day^{-1} or hr^{-1})

$\kappa_{3,20}$ Settling loss rate of CBOD at 20°C (day^{-1} or hr^{-1})

κ_4 Sediment oxygen demand rate (mg O$_2$/(m^2·day))

$\kappa_{4,20}$ Sediment oxygen demand rate at 20°C (mg O$_2$/(m^2·day) or mg O$_2$/(m^2·hr))

ρ_a Local respiration rate of algae (day^{-1} or hr^{-1})

$\rho_{a,20}$ Local algal respiration rate at 20°C (day^{-1} or hr^{-1})

σ_1 Local settling rate for algae (m/day or m/hr)

$\sigma_{1,20}$ Local algal settling rate at 20°C (m/day or m/hr)

σ_2 Benthos (sediment) source rate for soluble P (mg P/m^2-day or mg P/m^2-hr)

$\sigma_{2,20}$ Benthos (sediment) source rate for soluble phosphorus at 20°C (mg P/m^2-day or mg P/m^2-hr)

σ_3 Benthos (sediment) source rate for ammonium (mg N/m^2-day or mg N/m^2-hr)

$\sigma_{3,20}$ Benthos (sediment) source rate for ammonium nitrogen at 20°C (mg N/m^2-day or mg N/m^2-hr)

σ_4 Rate coefficient of organic nitrogen settling (day^{-1} or hr^{-1})

$\sigma_{4,20}$ Local settling rate for organic nitrogen at 20°C (day^{-1} or hr^{-1})

σ_5 Rate coefficient for organic phosphorus settling (day^{-1} or hr^{-1})

$\sigma_{5,20}$ Local settling rate for organic phosphorus at 20°C (day^{-1} or hr^{-1})

μ_a Local specific growth rate of algae (day^{-1} or hr^{-1})

$\mu_{a,20}$ Local specific algal growth rate at 20°C (day^{-1} or hr^{-1})

μ_{max} Maximum specific algal growth rate (day^{-1} or hr^{-1})

25.7 REFERENCES

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CHAPTER 26

EQUATIONS:
IN-STREAM PESTICIDE
TRANSFORMATIONS

SWAT incorporates a simple mass balance developed by Chapra (1997) to model the transformation and transport of pesticides in streams. The model assumes a well-mixed layer of water overlying a sediment layer. Only one pesticide can be routed through the stream network. The pesticide to be routed is defined by the variable IRTPEST in the .bsn file.

26.1 PESTICIDE IN THE WATER

Pesticide in a reach segment is increased through addition of mass in inflow as well as resuspension and diffusion of pesticide from the sediment layer. The amount of pesticide in a reach segment is reduced through removal in outflow as well as degradation, volatilization, settling and diffusion into the underlying sediment.

26.1.1 SOLID-LIQUID PARTITIONING

Pesticides will partition into particulate and dissolved forms. The fraction of pesticide in each phase is a function of the pesticide's partition coefficient and the reach segment's suspended solid concentration:

$$F_d = \frac{1}{1 + K_d \cdot conc_{sed}}$$
$$\text{26.1.1}$$

$$F_p = \frac{K_d \cdot conc_{sed}}{1 + K_d \cdot conc_{sed}} = 1 - F_d$$
$$\text{26.1.2}$$

where F_d is the fraction of total pesticide in the dissolved phase, F_p is the fraction of total pesticide in the particulate phase, K_d is the pesticide partition coefficient (m^3/g), and $conc_{sed}$ is the concentration of suspended solids in the water (g/m^3).

The pesticide partition coefficient can be estimated from the octanol-water partition coefficient (Chapra, 1997):

$$K_d = 3.085 \times 10^{-8} \cdot K_{ow}$$
$$\text{26.1.3}$$

where K_d is the pesticide partition coefficient (m^3/g) and K_{ow} is the pesticide's octanol-water partition coefficient ($mg\,m_{octanol}^{-3} \left(mg\,m_{water}^{-3}\right)^{-1}$). Values for the octanol-water partition coefficient have been published for many chemicals. If a published value cannot be found, it can be estimated from solubility (Chapra, 1997):

$$\log(K_{ow}) = 5.00 - 0.670 \cdot \log(pst'_{sol})$$
$$\text{26.1.4}$$

where pst'_{sol} is the pesticide solubility (µmoles/L). The solubility in these units is calculated:

$$pst'_{sol} = \frac{pst_{sol}}{MW} \cdot 10^3$$ 26.1.5

where pst'_{sol} is the pesticide solubility (µmoles/L), pst_{sol} is the pesticide solubility (mg/L) and MW is the molecular weight (g/mole).

26.1.2 DEGRADATION

Pesticides in both the particulate and dissolved forms are subject to degradation. The amount of pesticide that is removed from the water via degradation is:

$$pst_{deg,wtr} = k_{p,aq} \cdot pst_{rchwtr} \cdot TT$$ 26.1.6

where $pst_{deg,wtr}$ is the amount of pesticide removed from the water via degradation (mg pst), $k_{p,aq}$ is the rate constant for degradation or removal of pesticide in the water (1/day), pst_{rchwtr} is the amount of pesticide in the water at the beginning of the day (mg pst), and TT is the flow travel time (days). The rate constant is related to the aqueous half-life:

$$k_{p,aq} = \frac{0.693}{t_{1/2,aq}}$$ 26.1.7

where $k_{p,aq}$ is the rate constant for degradation or removal of pesticide in the water (1/day), and $t_{1/2,aq}$ is the aqueous half-life for the pesticide (days).

26.1.3 VOLATILIZATION

Pesticide in the dissolved phase is available for volatilization. The amount of pesticide removed from the water via volatilization is:

$$pst_{vol,wtr} = \frac{v_v}{depth} \cdot F_d \cdot pst_{rchwtr} \cdot TT$$ 26.1.8

where $pst_{vol,wtr}$ is the amount of pesticide removed via volatilization (mg pst), v_v is the volatilization mass-transfer coefficient (m/day), $depth$ is the flow depth (m), F_d is the fraction of total pesticide in the dissolved phase, pst_{rchwtr} is the amount of pesticide in the water (mg pst), and TT is the flow travel time (days).

The volatilization mass-transfer coefficient can be calculated based on Whitman's two-film or two-resistance theory (Whitman, 1923; Lewis and Whitman, 1924 as described in Chapra, 1997). While the main body of the gas and liquid phases are assumed to be well-mixed and homogenous, the two-film

theory assumes that a substance moving between the two phases encounters maximum resistance in two laminar boundary layers where transfer is a function of molecular diffusion. In this type of system the transfer coefficient or velocity is:

$$v_v = K_l \cdot \frac{H_e}{H_e + R \cdot T_K \cdot \left(K_l / K_g\right)} \qquad 26.1.9$$

where v_v is the volatilization mass-transfer coefficient (m/day), K_l is the mass-transfer velocity in the liquid laminar layer (m/day), K_g is the mass-transfer velocity in the gaseous laminar layer (m/day), H_e is Henry's constant (atm m^3 mole^{-1}), R is the universal gas constant (8.206×10^{-5} atm m^3 (K mole)$^{-1}$), and T_K is the temperature (K).

For rivers where liquid flow is turbulent, the transfer coefficients are estimated using the surface renewal theory (Higbie, 1935; Danckwerts, 1951; as described by Chapra, 1997). The surface renewal model visualizes the system as consisting of parcels of water that are brought to the surface for a period of time. The fluid elements are assumed to reach and leave the air/water interface randomly, i.e. the exposure of the fluid elements to air is described by a statistical distribution. The transfer velocities for the liquid and gaseous phases are calculated:

$$K_l = \sqrt{r_l \cdot D_l} \qquad\qquad K_g = \sqrt{r_g \cdot D_g} \qquad 26.1.10$$

where K_l is the mass-transfer velocity in the liquid laminar layer (m/day), K_g is the mass-transfer velocity in the gaseous laminar layer (m/day), D_l is the liquid molecular diffusion coefficient (m^2/day), D_g is the gas molecular diffusion coefficient (m^2/day), r_l is the liquid surface renewal rate (1/day), and r_g is the gaseous surface renewal rate (1/day).

O'Connor and Dobbins (1956) defined the surface renewal rate as the ratio of the average stream velocity to depth.

$$r_l = \frac{86400 \cdot v_c}{depth} \qquad 26.1.11$$

where r_l is the liquid surface renewal rate (1/day), v_c is the average stream velocity (m/s) and *depth* is the depth of flow (m).

26.1.4 SETTLING

Pesticide in the particulate phase may be removed from the water layer by settling. Settling transfers pesticide from the water to the sediment layer. The amount of pesticide that is removed from the water via settling is:

$$pst_{stl,wtr} = \frac{v_s}{depth} \cdot F_p \cdot pst_{rchwtr} \cdot TT \qquad 26.1.12$$

where $pst_{stl,wtr}$ is the amount of pesticide removed from the water due to settling (mg pst), v_s is the settling velocity (m/day), *depth* is the flow depth (m), F_p is the fraction of total pesticide in the particulate phase, pst_{rchwtr} is the amount of pesticide in the water (mg pst), and *TT* is the flow travel time (days).

26.1.5 OUTFLOW

Pesticide is removed from the reach segment in outflow. The amount of dissolved and particulate pesticide removed from the reach segment in outflow is:

$$pst_{sol,o} = Q \cdot \frac{F_d \cdot pst_{rchwtr}}{V} \qquad 26.1.13$$

$$pst_{sorb,o} = Q \cdot \frac{F_p \cdot pst_{rchwtr}}{V} \qquad 26.1.14$$

where $pst_{sol,o}$ is the amount of dissolved pesticide removed via outflow (mg pst), $pst_{sorb,o}$ is the amount of particulate pesticide removed via outflow (mg pst), Q is the rate of outflow from the reach segment (m³ H_2O/day), F_d is the fraction of total pesticide in the dissolved phase, F_p is the fraction of total pesticide in the particulate phase, pst_{rchwtr} is the amount of pesticide in the water (mg pst), and V is the volume of water in the reach segment (m³ H_2O).

Table 26-1: SWAT input variables that pesticide partitioning.

Variable Name	Definition	Input File
CHPST_KOC	K_d: Pesticide partition coefficient (m³/g)	.swq
CHPST_REA	$k_{p,aq}$: Rate constant for degradation or removal of pesticide in the water (1/day)	.swq
CHPST_VOL	v_v: Volatilization mass-transfer coefficient (m/day)	.swq
CHPST_STL	v_s: Pesticide settling velocity (m/day)	.swq

26.2 PESTICIDE IN THE SEDIMENT

Pesticide in the sediment layer underlying a reach segment is increased through addition of mass by settling and diffusion from the water. The amount of pesticide in the sediment layer is reduced through removal by degradation, resuspension, diffusion into the overlying water, and burial.

26.2.1 SOLID-LIQUID PARTITIONING

As in the water layer, pesticides in the sediment layer will partition into particulate and dissolved forms. Calculation of the solid-liquid partitioning in the sediment layer requires a suspended solid concentration. The "concentration" of solid particles in the sediment layer is defined as:

$$conc^*_{sed} = \frac{M_{sed}}{V_{tot}}$$
26.2.1

where $conc^*_{sed}$ is the "concentration" of solid particles in the sediment layer (g/m^3), M_{sed} is the mass of solid particles in the sediment layer (g) and V_{tot} is the total volume of the sediment layer (m^3).

Mass and volume are also used to define the porosity and density of the sediment layer. In the sediment layer, porosity is the fraction of the total volume in the liquid phase:

$$\phi = \frac{V_{wtr}}{V_{tot}}$$
26.2.2

where ϕ is the porosity, V_{wtr} is the volume of water in the sediment layer (m^3) and V_{tot} is the total volume of the sediment layer (m^3). The fraction of the volume in the solid phase can then be defined as:

$$1 - \phi = \frac{V_{sed}}{V_{tot}}$$
26.2.3

where ϕ is the porosity, V_{sed} is the volume of solids in the sediment layer (m^3) and V_{tot} is the total volume of the sediment layer (m^3).

The density of sediment particles is defined as:

$$\rho_s = \frac{M_{sed}}{V_{sed}}$$
26.2.4

where ρ_s is the particle density (g/m^3), M_{sed} is the mass of solid particles in the sediment layer (g), and V_{sed} is the volume of solids in the sediment layer (m^3).

Solving equation 26.2.3 for V_{tot} and equation 26.2.4 for M_{sed} and substituting into equation 26.2.1 yields:

$$conc^*_{sed} = (1 - \phi) \cdot \rho_s \qquad\qquad 26.2.5$$

where $conc^*_{sed}$ is the "concentration" of solid particles in the sediment layer (g/m^3), ϕ is the porosity, and ρ_s is the particle density (g/m^3).

Assuming $\phi = 0.5$ and $\rho_s = 2.6 \times 10^6$ g/m^3, the "concentration" of solid particles in the sediment layer is 1.3×10^6 g/m^3.

The fraction of pesticide in each phase is then calculated:

$$F_{d,sed} = \frac{1}{\phi + (1 - \phi) \cdot \rho_s \cdot K_d} \qquad\qquad 26.2.6$$

$$F_{p,sed} = 1 - F_{d,sed} \qquad\qquad 26.2.7$$

where $F_{d,sed}$ is the fraction of total sediment pesticide in the dissolved phase, $F_{p,sed}$ is the fraction of total sediment pesticide in the particulate phase, ϕ is the porosity, ρ_s is the particle density (g/m^3), and K_d is the pesticide partition coefficient (m^3/g). The pesticide partition coefficient used for the water layer is also used for the sediment layer.

26.2.2 DEGRADATION

Pesticides in both the particulate and dissolved forms are subject to degradation. The amount of pesticide that is removed from the sediment via degradation is:

$$pst_{deg,sed} = k_{p,sed} \cdot pst_{rchsed} \qquad\qquad 26.2.8$$

where $pst_{deg,sed}$ is the amount of pesticide removed from the sediment via degradation (mg pst), $k_{p,sed}$ is the rate constant for degradation or removal of pesticide in the sediment (1/day), and pst_{rchsed} is the amount of pesticide in the sediment (mg pst). The rate constant is related to the sediment half-life:

$$k_{p,sed} = \frac{0.693}{t_{1/2,sed}} \qquad\qquad 26.2.9$$

where $k_{p,sed}$ is the rate constant for degradation or removal of pesticide in the sediment (1/day), and $t_{1/2,sed}$ is the sediment half-life for the pesticide (days).

26.2.3 RESUSPENSION

Pesticide in the sediment layer is available for resuspension. The amount of pesticide that is removed from the sediment via resuspension is:

$$pst_{rsp,wtr} = \frac{v_r}{depth} \cdot pst_{rchsed} \cdot TT \qquad 26.2.10$$

where $pst_{rsp,wtr}$ is the amount of pesticide removed via resuspension (mg pst), v_r is the resuspension velocity (m/day), *depth* is the flow depth (m), pst_{rchsed} is the amount of pesticide in the sediment (mg pst), and *TT* is the flow travel time (days). Pesticide removed from the sediment layer by resuspension is added to the water layer.

26.2.4 DIFFUSION

Pesticide in the dissolved phase is available for diffusion. Diffusion transfers pesticide between the water and sediment layers. The direction of movement is controlled by the pesticide concentration. Pesticide will move from areas of high concentration to areas of low concentration. The amount of pesticide that is transferred between the water and sediment by diffusion is:

$$pst_{dif} = \left| \frac{v_d}{depth} \cdot \left(F_{d,sed} \cdot pst_{rchsed} - F_d \cdot pst_{rchwtr} \right) \cdot TT \right| \qquad 26.2.11$$

where pst_{dif} is the amount of pesticide transferred between the water and sediment by diffusion (mg pst), v_d is the rate of diffusion or mixing velocity (m/day), *depth* is the flow depth (m), $F_{d,sed}$ is the fraction of total sediment pesticide in the dissolved phase, pst_{rchsed} is the amount of pesticide in the sediment (mg pst), F_d is the fraction of total water layer pesticide in the dissolved phase, pst_{rchwtr} is the amount of pesticide in the water (mg pst), and *TT* is the flow duration (days). If $F_{d,sed} \cdot pst_{rchsed} > F_d \cdot pst_{rchwtr}$, pst_{dif} is transferred from the sediment to the water layer. If, $F_{d,sed} \cdot pst_{rchsed} < F_d \cdot pst_{rchwtr}$, pst_{dif} is transferred from the water to the sediment layer.

The diffusive mixing velocity, v_d, can be estimated from the empirically derived formula (Chapra, 1997):

$$v_d = \frac{69.35}{365} \cdot \phi \cdot MW^{-2/3} \qquad 26.2.12$$

where v_d is the rate of diffusion or mixing velocity (m/day), ϕ is the sediment porosity, and MW is the molecular weight of the pesticide compound.

26.2.5 BURIAL

Pesticide in the sediment layer may be lost by burial. The amount of pesticide that is removed from the sediment via burial is:

$$pst_{bur} = \frac{v_b}{D_{sed}} \cdot pst_{rchsed} \qquad 26.2.13$$

where pst_{bur} is the amount of pesticide removed via burial (mg pst), v_b is the burial velocity (m/day), D_{sed} is the depth of the active sediment layer (m), and pst_{rchsed} is the amount of pesticide in the sediment (mg pst).

Table 26-2: SWAT input variables related to pesticide in the sediment.

Variable Name	Definition	Input File
CHPST_KOC	K_d: Pesticide partition coefficient (m³/g)	.swq
SEDPST_REA	$k_{p,sed}$: Rate constant for degradation or removal of pesticide in the sediment (1/day)	.swq
CHPST_RSP	v_r: Resuspension velocity (m/day)	.swq
SEDPST_ACT	D_{sed}: Depth of the active sediment layer (m)	.swq
CHPST_MIX	v_d: Rate of diffusion or mixing velocity (m/day)	.swq
SEDPST_BRY	v_b: Pesticide burial velocity (m/day)	.swq

26.3 MASS BALANCE

The processes described above can be combined into mass balance equations for the well-mixed reach segment and the well-mixed sediment layer:

$$\Delta pst_{rchwtr} = pst_{in} - \left(pst_{sol,o} + pst_{sorb,o}\right) - pst_{deg,wtr} - pst_{vol,wtr}$$

$$- pst_{stl,wtr} + pst_{rsp,wtr} \pm pst_{dif} \quad 26.3.1$$

$$\Delta pst_{rchsed} = - pst_{deg,sed} + pst_{stl,wtr} - pst_{rsp,wtr} - pst_{bur} \pm pst_{dif} \qquad 26.3.2$$

where Δpst_{rchwtr} is the change in pesticide mass in the water layer (mg pst), Δpst_{rchsed} is the change in pesticide mass in the sediment layer (mg pst), pst_{in} is the

pesticide added to the reach segment via inflow (mg pst), $pst_{sol,o}$ is the amount of dissolved pesticide removed via outflow (mg pst), $pst_{sorb,o}$ is the amount of particulate pesticide removed via outflow (mg pst), $pst_{deg,wtr}$ is the amount of pesticide removed from the water via degradation (mg pst), $pst_{vol,wtr}$ is the amount of pesticide removed via volatilization (mg pst), $pst_{stl,wtr}$ is the amount of pesticide removed from the water due to settling (mg pst), $pst_{rsp,wtr}$ is the amount of pesticide removed via resuspension (mg pst), pst_{dif} is the amount of pesticide transferred between the water and sediment by diffusion (mg pst), $pst_{deg,sed}$ is the amount of pesticide removed from the sediment via degradation (mg pst), pst_{bur} is the amount of pesticide removed via burial (mg pst)

26.4 NOMENCLATURE

D_g Gas molecular diffusion coefficient (m^2/day)
D_l Liquid molecular diffusion coefficient (m^2/day)
D_{sed} Depth of the active sediment layer (m)
F_d Fraction of total pesticide in the dissolved phase
$F_{d,sed}$ Fraction of total sediment pesticide in the dissolved phase
F_p Fraction of total pesticide in the particulate phase
$F_{p,sed}$ Fraction of total sediment pesticide in the particulate phase
H_e Henry's constant (atm m^3 mole^{-1})
K_d Pesticide partition coefficient (m^3/g)
K_g Mass-transfer velocity in the gaseous laminar layer (m/day)
K_l Mass-transfer velocity in the liquid laminar layer (m/day)
M_{sed} Mass of solid phase in the sediment layer (g)
MW Molecular weight of the pesticide compound
Q Rate of outflow from the reach segment (m^3 H$_2$O/day)
R Universal gas constant (8.206 × 10^{-5} atm m^3 (K mole)$^{-1}$)
V_{sed} Volume of solids in the sediment layer (m^3)
V_{tot} Total volume of the sediment layer (m^3)
V_{wtr} Volume of water in the sediment layer (m^3)

$conc_{sed}$ Concentration of suspended solids in the water (g/m^3)
$conc_{sed}^{*}$ "Concentration" of solid particles in the sediment layer (g/m^3)
$depth$ Depth of flow (m)
$k_{p,aq}$ Rate constant for degradation or removal of pesticide in the water (1/day)
$k_{p,sed}$ Rate constant for degradation or removal of pesticide in the sediment (1/day)
pst_{bur} Amount of pesticide removed via burial (mg pst)
$pst_{deg,sed}$ Amount of pesticide removed from the sediment via degradation (mg pst)

$pst_{deg,wtr}$ Amount of pesticide removed from the water via degradation (mg pst)

pst_{dif} Amount of pesticide transferred between the water and sediment by diffusion (mg pst)

pst_{rchsed} Amount of pesticide in the sediment (mg pst)

pst_{rchwtr} Amount of pesticide in the water (mg pst)

$pst_{rsp,wtr}$ Amount of pesticide removed from sediment via resuspension (mg pst)

$pst_{sol,o}$ Amount of dissolved pesticide removed via outflow (mg pst)

$pst_{sorb,o}$ Amount of particulate pesticide removed via outflow (mg pst)

$pst_{stl,wtr}$ Amount of pesticide removed from the water due to settling (mg pst)

$pst_{vol,wtr}$ Amount of pesticide removed via volatilization (mg pst)

r_g Gaseous surface renewal rate (1/day)

r_l Liquid surface renewal rate (1/day)

$t_{1/2,aq}$ Aqueous half-life for the pesticide (days)

$t_{1/2,sed}$ Sediment half-life for the pesticide (days)

v_b Pesticide burial velocity (m/day)

v_c Average stream velocity (m/s)

v_d Rate of diffusion or mixing velocity (m/day)

v_r Resuspension velocity (m/day)

v_s Settling velocity (m/day)

v_v Volatilization mass-transfer coefficient (m/day)

Δpst_{rchwtr} Change in pesticide mass in the water layer (mg pst)

Δpst_{rchsed} Change in pesticide mass in the sediment layer (mg pst)

ϕ Porosity

ρ_s Particle density (g/m^3)

26.5 REFERENCES

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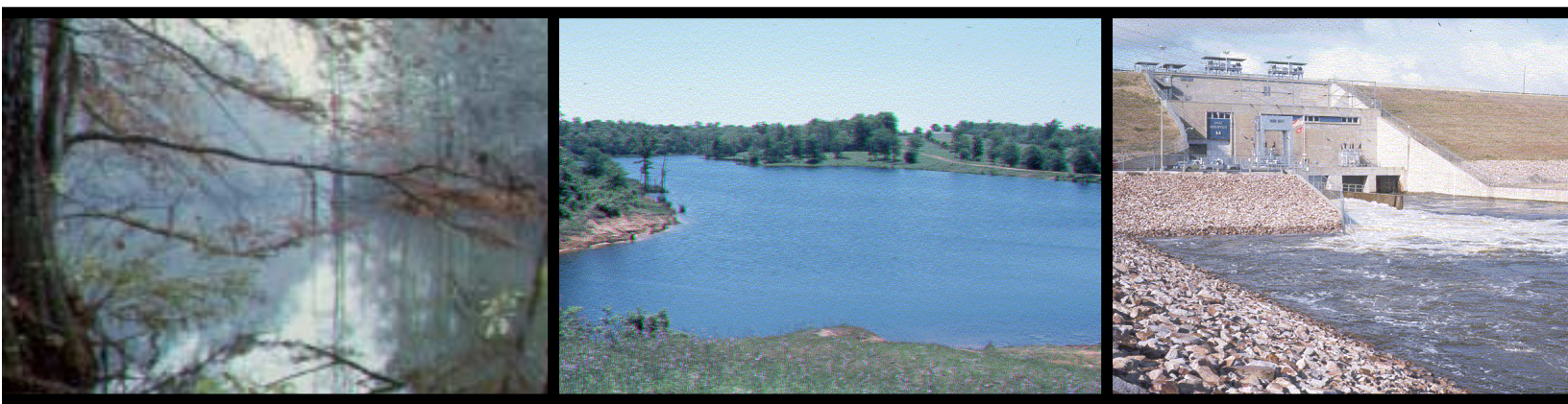
WATER BODIES

       Impoundment structures modify the movement of water in the channel network by lowering the peak flow and volume of flood discharges. Because impoundments slow down the flow of water, sediment will fall from suspension, removing nutrient and chemicals adsorbed to the soil particles.

CHAPTER **27**

EQUATIONS: IMPOUNDMENT WATER ROUTING

Impoundments play an important role in water supply and flood control. SWAT models four types of water bodies: ponds, wetlands, depressions/potholes, and reservoirs. Ponds, wetlands, and depressions/potholes are located within a subbasin off the main channel. Water flowing into these water bodies must originate from the subbasin in which the water body is located. Reservoirs are located on the main channel network. They receive water from all subbasins upstream of the water body.

27.1 RESERVOIRS

A reservoir is an impoundment located on the main channel network of a watershed. No distinction is made between naturally-occurring and man-made structures. The features of an impoundment are shown in Figure 27.1.
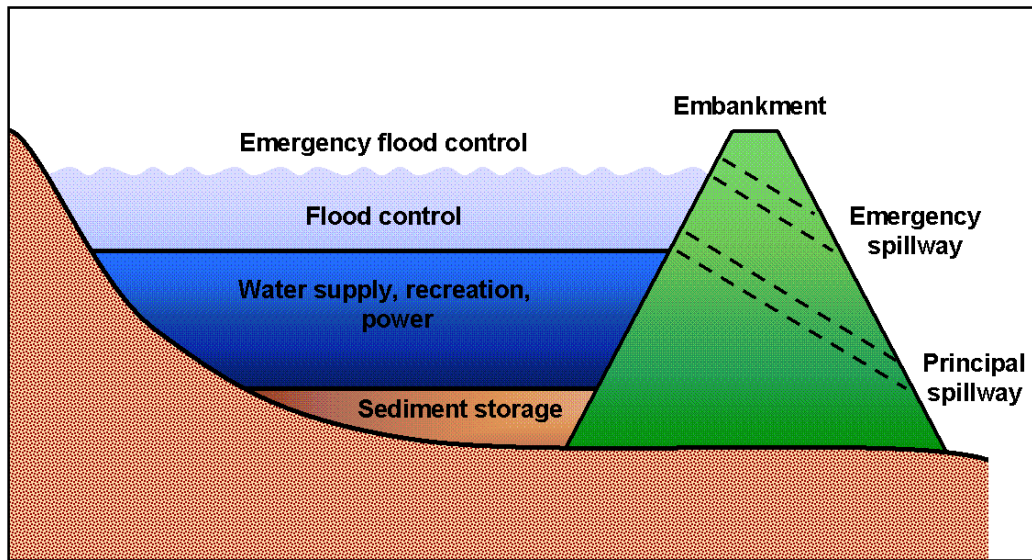
Figure 27.1: Components of a reservoir with flood water detention features.

The water balance for a reservoir is:

$$V = V_{stored} + V_{flowin} - V_{flowout} + V_{pcp} - V_{evap} - V_{seep} \qquad 27.1.1$$

where V is the volume of water in the impoundment at the end of the day (m^3 H$_2$O), V_{stored} is the volume of water stored in the water body at the beginning of the day (m^3 H$_2$O), V_{flowin} is the volume of water entering the water body during the day (m^3 H$_2$O), $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H$_2$O), V_{pcp} is the volume of precipitation falling on the water body during the day (m^3 H$_2$O), V_{evap} is the volume of water removed from the water body by evaporation during the day (m^3 H$_2$O), and V_{seep} is the volume of water lost from the water body by seepage (m^3 H$_2$O).

27.1.1 SURFACE AREA

The surface area of the reservoir is needed to calculate the amount of precipitation falling on the water body as well as the amount of evaporation and seepage. Surface area varies with change in the volume of water stored in the reservoir. The surface area is updated daily using the equation:

$$SA = \beta_{sa} \cdot V^{expsa} \qquad\qquad 27.1.2$$

where SA is the surface area of the water body (ha), β_{sa} is a coefficient, V is the volume of water in the impoundment (m^3 H_2O), and $expsa$ is an exponent.

The coefficient, β_{sa}, and exponent, $expsa$, are calculated by solving equation 27.1.2 using two known points. The two known points are surface area and volume information provided for the principal and emergency spillways.

$$expsa = \frac{\log_{10}(SA_{em}) - \log_{10}(SA_{pr})}{\log_{10}(V_{em}) - \log_{10}(V_{pr})} \qquad\qquad 27.1.3$$

$$\beta_{sa} = \left(\frac{SA_{em}}{V_{em}}\right)^{expsa} \qquad\qquad 27.1.4$$

where SA_{em} is the surface area of the reservoir when filled to the emergency spillway (ha), SA_{pr} is the surface area of the reservoir when filled to the principal spillway (ha), V_{em} is the volume of water held in the reservoir when filled to the emergency spillway (m^3 H_2O), and V_{pr} is the volume of water held in the reservoir when filled to the principal spillway (m^3 H_2O).

27.1.2 PRECIPITATION

The volume of precipitation falling on the reservoir during a given day is calculated:

$$V_{pcp} = 10 \cdot R_{day} \cdot SA \qquad\qquad 27.1.5$$

where V_{pcp} is the volume of water added to the water body by precipitation during the day (m^3 H_2O), R_{day} is the amount of precipitation falling on a given day (mm H_2O), and SA is the surface area of the water body (ha).

27.1.3 EVAPORATION

The volume of water lost to evaporation on a given day is calculated:

$$V_{evap} = 10 \cdot \eta \cdot E_o \cdot SA \qquad\qquad 27.1.6$$

where V_{evap} is the volume of water removed from the water body by evaporation during the day (m^3 H$_2$O), η is an evaporation coefficient (0.6), E_o is the potential evapotranspiration for a given day (mm H$_2$O), and SA is the surface area of the water body (ha).

27.1.4 SEEPAGE

The volume of water lost by seepage through the bottom of the reservoir on a given day is calculated:

$$V_{seep} = 240 \cdot K_{sat} \cdot SA \qquad\qquad 27.1.7$$

where V_{seep} is the volume of water lost from the water body by seepage (m^3 H$_2$O), K_{sat} is the effective saturated hydraulic conductivity of the reservoir bottom (mm/hr), and SA is the surface area of the water body (ha).

27.1.5 OUTFLOW

The volume of outflow may be calculated using one of four different methods: measured daily outflow, measured monthly outflow, average annual release rate for uncontrolled reservoir, controlled outflow with target release.

27.1.5.1 MEASURED DAILY OUTFLOW

When measured daily outflow (IRESCO = 3) is chosen as the method to calculate reservoir outflow, the user must provide a file with the outflow rate for every day the reservoir is simulated in the watershed. The volume of outflow from the reservoir is then calculated:

$$V_{flowout} = 86400 \cdot q_{out} \qquad\qquad 27.1.8$$

where $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H$_2$O), and q_{out} is the outflow rate (m^3/s).

27.1.5.2 MEASURED MONTHLY OUTFLOW

When measured monthly outflow (IRESCO = 1) is chosen as the method to calculate reservoir outflow, the user must provide a file with the average daily outflow rate for every month the reservoir is simulated in the watershed. The volume of outflow from the reservoir is then calculated using equation 27.1.8.

27.1.5.3 AVERAGE ANNUAL RELEASE RATE

FOR UNCONTROLLED RESERVOIR

When the average annual release rate (IRESCO = 0) is chosen as the method to calculate reservoir outflow, the reservoir releases water whenever the reservoir volume exceeds the principal spillway volume, V_{pr}. If the reservoir volume is greater than the principal spillway volume but less than the emergency spillway volume, the amount of reservoir outflow is calculated:

$$V_{flowout} = V - V_{pr} \qquad \text{if } V - V_{pr} < q_{rel} \cdot 86400 \qquad 27.1.9$$

$$V_{flowout} = q_{rel} \cdot 86400 \qquad \text{if } V - V_{pr} > q_{rel} \cdot 86400 \qquad 27.1.10$$

If the reservoir volume exceeds the emergency spillway volume, the amount of outflow is calculated:

$$V_{flowout} = (V - V_{em}) + (V_{em} - V_{pr})$$

$$\text{if } V_{em} - V_{pr} < q_{rel} \cdot 86400 \qquad 27.1.11$$

$$V_{flowout} = (V - V_{em}) + q_{rel} \cdot 86400$$

$$\text{if } V_{em} - V_{pr} > q_{rel} \cdot 86400 \qquad 27.1.12$$

where $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H$_2$O), V is the volume of water stored in the reservoir (m^3 H$_2$O), V_{pr} is the volume of water held in the reservoir when filled to the principal spillway (m^3 H$_2$O), V_{em} is the volume of water held in the reservoir when filled to the emergency spillway (m^3 H$_2$O), and q_{rel} is the average daily principal spillway release rate (m^3/s).

27.1.5.4 TARGET RELEASE FOR CONTROLLED RESERVOIR

When target release (IRESCO = 2) is chosen as the method to calculate reservoir outflow, the reservoir releases water as a function of the desired target storage.

The target release approach tries to mimic general release rules that may be used by reservoir operators. Although the method is simplistic and cannot account for all decision criteria, it can realistically simulate major outflow and low flow periods.

For the target release approach, the principal spillway volume corresponds to maximum flood control reservation while the emergency spillway volume corresponds to no flood control reservation. The model requires the beginning and ending month of the flood season. In the non-flood season, no flood control reservation is required, and the target storage is set at the emergency spillway volume. During the flood season, the flood control reservation is a function of soil water content. The flood control reservation for wet ground conditions is set at the maximum. For dry ground conditions, the flood control reservation is set at 50% of the maximum.

The target storage may be specified by the user on a monthly basis or it can be calculated as a function of flood season and soil water content. If the target storage is specified:

$$V_{targ} = starg \qquad\qquad 27.1.13$$

where V_{targ} is the target reservoir volume for a given day (m^3 H$_2$O), and *starg* is the target reservoir volume specified for a given month (m^3 H$_2$O). If the target storage is not specified, the target reservoir volume is calculated:

$$V_{targ} = V_{em} \qquad\qquad \text{if } mon_{fld,beg} < mon < mon_{fld,end} \qquad 27.1.14$$

$$V_{targ} = V_{pr} + \frac{\left(1 - \min\left[\dfrac{SW}{FC}, \ 1\right]\right)}{2} \cdot \left(V_{em} - V_{pr}\right)$$

$$\text{if } mon \leq mon_{fld,beg} \text{ or } mon \geq mon_{fld,end} \qquad 27.1.15$$

where V_{targ} is the target reservoir volume for a given day (m^3 H$_2$O), V_{em} is the volume of water held in the reservoir when filled to the emergency spillway (m^3 H$_2$O), V_{pr} is the volume of water held in the reservoir when filled to the principal spillway (m^3 H$_2$O), SW is the average soil water content in the subbasin (mm H$_2$O), FC is the water content of the subbasin soil at field capacity (mm H$_2$O), mon is the month of the year, $mon_{fld,beg}$ is the beginning month of the flood season, and $mon_{fld,end}$ is the ending month of the flood season.

Once the target storage is defined, the outflow is calculated:

$$V_{flowout} = \frac{V - V_{targ}}{ND_{targ}} \qquad 27.1.16$$

where $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H$_2$O), V is the volume of water stored in the reservoir (m^3 H$_2$O), V_{targ} is the target reservoir volume for a given day (m^3 H$_2$O), and ND_{targ} is the number of days required for the reservoir to reach target storage.

Once outflow is determined using one of the preceding four methods, the user may specify maximum and minimum amounts of discharge that the initial outflow estimate is checked against. If the outflow doesn't meet the minimum discharge or exceeds the maximum specified discharge, the amount of outflow is altered to meet the defined criteria.

$$V_{flowout} = V'_{flowout} \qquad \text{if } q_{rel,mn} \cdot 86400 \leq V'_{flowout} \leq q_{rel,mx} \cdot 86400 \qquad 27.1.17$$

$$V_{flowout} = q_{rel,mn} \cdot 86400 \qquad \text{if } V'_{flowout} < q_{rel,mn} \cdot 86400 \qquad 27.1.18$$

$$V_{flowout} = q_{rel,mx} \cdot 86400 \qquad \text{if } V'_{flowout} > q_{rel,mx} \cdot 86400 \qquad 27.1.19$$

where $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H$_2$O), $V'_{flowout}$ is the initial estimate of the volume of water flowing out of the water body during the day (m^3 H$_2$O), $q_{rel,mn}$ is the minimum average daily outflow for the month (m^3/s), and $q_{rel,mx}$ is the maximum average daily outflow for the month (m^3/s).

Table 27-1: SWAT input variables that pertain to reservoirs.

Variable name	Definition	File Name
RES_ESA	SA_{em}: Surface area of the reservoir when filled to the emergency spillway (ha)	.res
RES_PSA	SA_{pr}: Surface area of the reservoir when filled to the principal spillway (ha)	.res
RES_EVOL	V_{em}: Volume of water held in the reservoir when filled to the emergency spillway (10^4 m^3 H$_2$O)	.res
RES_PVOL	V_{pr}: Volume of water held in the reservoir when filled to the principal spillway (10^4 m^3 H$_2$O)	.res
RES_K	K_{sat}: Effective saturated hydraulic conductivity of the reservoir bottom (mm/hr)	.res
IRESCO	Outflow method	.res
RES_OUTFLOW	q_{out}: Outflow rate (m^3/s)	resdayo.dat
RESOUT	q_{out}: Outflow rate (m^3/s)	resmono.dat
RES_RR	q_{rel}: Average daily principal spillway release rate (m^3/s)	.res
STARG(mon)	$starg$: Target reservoir volume specified for a given month (m^3 H$_2$O)	.res
IFLOD1R	$mon_{fld,beg}$: Beginning month of the flood season	.res
IFLOD2R	$mon_{fld,end}$: Ending month of the flood season	.res
NDTARGR	ND_{targ}: Number of days required for the reservoir to reach target storage	.res
OFLOWMN(mon)	$q_{rel,mn}$: Minimum average daily outflow for the month (m^3/s)	.res
OFLOWMX(mon)	$q_{rel,mx}$: Maximum average daily outflow for the month (m^3/s)	.res

27.2 PONDS/WETLANDS

Ponds and wetlands are water bodies located within subbasins that received inflow from a fraction of the subbasin area. The algorithms used to model these two types of water bodies differ only in the options allowed for outflow calculation.

The water balance for a pond or wetland is:

$$V = V_{stored} + V_{flowin} - V_{flowout} + V_{pcp} - V_{evap} - V_{seep}$$ 27.2.1

where V is the volume of water in the impoundment at the end of the day (m^3 H$_2$O), V_{stored} is the volume of water stored in the water body at the beginning of the day (m^3 H$_2$O), V_{flowin} is the volume of water entering the water body during the day (m^3 H$_2$O), $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H$_2$O), V_{pcp} is the volume of precipitation falling on the water body during the day (m^3 H$_2$O), V_{evap} is the volume of water removed from the water body by evaporation during the day (m^3 H$_2$O), and V_{seep} is the volume of water lost from the water body by seepage (m^3 H$_2$O).

27.2.1 SURFACE AREA

The surface area of the pond or wetland is needed to calculate the amount of precipitation falling on the water body as well as the amount of evaporation and seepage. Surface area varies with change in the volume of water stored in the impoundment. The surface area is updated daily using the equation:

$$SA = \beta_{sa} \cdot V^{expsa} \qquad\qquad 27.2.2$$

where SA is the surface area of the water body (ha), β_{sa} is a coefficient, V is the volume of water in the impoundment (m^3 H_2O), and $expsa$ is an exponent.

The coefficient, β_{sa}, and exponent, $expsa$, are calculated by solving equation 27.1.2 using two known points. For ponds, the two known points are surface area and volume information provided for the principal and emergency spillways.

$$expsa = \frac{\log_{10}(SA_{em}) - \log_{10}(SA_{pr})}{\log_{10}(V_{em}) - \log_{10}(V_{pr})} \qquad\qquad 27.2.3$$

$$\beta_{sa} = \left(\frac{SA_{em}}{V_{em}}\right)^{expsa} \qquad\qquad 27.2.4$$

where SA_{em} is the surface area of the pond when filled to the emergency spillway (ha), SA_{pr} is the surface area of the pond when filled to the principal spillway (ha), V_{em} is the volume of water held in the pond when filled to the emergency spillway (m^3 H_2O), and V_{pr} is the volume of water held in the pond when filled to the principal spillway (m^3 H_2O). For wetlands, the two known points are surface area and volume information provided for the maximum and normal water levels.

$$expsa = \frac{\log_{10}(SA_{mx}) - \log_{10}(SA_{nor})}{\log_{10}(V_{mx}) - \log_{10}(V_{nor})} \qquad\qquad 27.2.5$$

$$\beta_{sa} = \left(\frac{SA_{mx}}{V_{mx}}\right)^{expsa} \qquad\qquad 27.2.6$$

where SA_{mx} is the surface area of the wetland when filled to the maximum water level (ha), SA_{nor} is the surface area of the wetland when filled to the normal water level (ha), V_{mx} is the volume of water held in the wetland when filled to the

maximum water level (m^3 H_2O), and V_{nor} is the volume of water held in the wetland when filled to the normal water level (m^3 H_2O).

27.2.2 PRECIPITATION

The volume of precipitation falling on the pond or wetland during a given day is calculated:

$$V_{pcp} = 10 \cdot R_{day} \cdot SA \qquad\qquad 27.2.7$$

where V_{pcp} is the volume of water added to the water body by precipitation during the day (m^3 H_2O), R_{day} is the amount of precipitation falling on a given day (mm H_2O), and SA is the surface area of the water body (ha).

27.2.3 INFLOW

The volume of water entering the pond or wetland on a given day is calculated:

$$V_{flowin} = fr_{imp} \cdot 10 \cdot \left(Q_{surf} + Q_{gw} + Q_{lat}\right) \cdot \left(Area - SA\right) \qquad\qquad 27.2.8$$

where V_{flowin} is the volume of water flowing into the water body on a given day (m^3 H_2O), fr_{imp} is the fraction of the subbasin area draining into the impoundment, Q_{surf} is the surface runoff from the subbasin on a given day (mm H_2O), Q_{gw} is the groundwater flow generated in a subbasin on a given day (mm H_2O), Q_{lat} is the lateral flow generated in a subbasin on a given day (mm H_2O), *Area* is the subbasin area (ha), and SA is the surface area of the water body (ha). The volume of water entering the pond or wetland is subtracted from the surface runoff, lateral flow and groundwater loadings to the main channel.

27.2.4 EVAPORATION

The volume of water lost to evaporation on a given day is calculated:

$$V_{evap} = 10 \cdot \eta \cdot E_o \cdot SA \qquad\qquad 27.2.9$$

where V_{evap} is the volume of water removed from the water body by evaporation during the day (m^3 H_2O), η is an evaporation coefficient (0.6), E_o is the potential evapotranspiration for a given day (mm H_2O), and SA is the surface area of the water body (ha).

27.2.5   SEEPAGE

The volume of water lost by seepage through the bottom of the pond or wetland on a given day is calculated:

$$V_{seep} = 240 \cdot K_{sat} \cdot SA \qquad\qquad 27.2.10$$

where V_{seep} is the volume of water lost from the water body by seepage (m^3 H$_2$O), K_{sat} is the effective saturated hydraulic conductivity of the pond or wetland bottom (mm/hr), and SA is the surface area of the water body (ha).

27.2.6   OUTFLOW

The primary difference between ponds and wetlands is the method in which the outflow is calculated.

27.2.6.1   POND OUTFLOW

Pond outflow is calculated as a function of target storage. The target storage varies based on flood season and soil water content. The target pond volume is calculated:

$$V_{targ} = V_{em} \qquad\qquad \text{if } mon_{fld,beg} < mon < mon_{fld,end} \qquad 27.2.11$$

$$V_{targ} = V_{pr} + \frac{\left(1 - \min\left[\dfrac{SW}{FC}, \; 1\right]\right)}{2} \cdot \left(V_{em} - V_{pr}\right)$$

$$\text{if } mon \leq mon_{fld,beg} \text{ or } mon \geq mon_{fld,end} \qquad 27.2.12$$

where V_{targ} is the target pond volume for a given day (m^3 H$_2$O), V_{em} is the volume of water held in the pond when filled to the emergency spillway (m^3 H$_2$O), V_{pr} is the volume of water held in the pond when filled to the principal spillway (m^3 H$_2$O), SW is the average soil water content in the subbasin (mm H$_2$O), FC is the water content of the subbasin soil at field capacity (mm H$_2$O), mon is the month of the year, $mon_{fld,beg}$ is the beginning month of the flood season, and $mon_{fld,end}$ is the ending month of the flood season.

Once the target storage is defined, the outflow is calculated:

$$V_{flowout} = \frac{V - V_{targ}}{ND_{targ}}$$ 27.2.13

where $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H$_2$O), V is the volume of water stored in the pond (m^3 H$_2$O), V_{targ} is the target pond volume for a given day (m^3 H$_2$O), and ND_{targ} is the number of days required for the pond to reach target storage.

27.2.6.2 WETLAND OUTFLOW

The wetland releases water whenever the water volume exceeds the normal storage volume, V_{nor}. Wetland outflow is calculated:

$$V_{flowout} = 0 \qquad\qquad \text{if } V < V_{nor} \qquad\qquad 27.2.14$$

$$V_{flowout} = \frac{V - V_{nor}}{10} \qquad\qquad \text{if } V_{nor} \leq V \leq V_{mx} \qquad\qquad 27.2.15$$

$$V_{flowout} = V - V_{mx} \qquad\qquad \text{if } V > V_{mx} \qquad\qquad 27.2.16$$

where $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H$_2$O), V is the volume of water stored in the wetland (m^3 H$_2$O), V_{mx} is the volume of water held in the wetland when filled to the maximum water level (m^3 H$_2$O), and V_{nor} is the volume of water held in the wetland when filled to the normal water level (m^3 H$_2$O).

Table 27-2: SWAT input variables that pertain to ponds and wetlands.

Variable name	Definition	File Name
PND_ESA	SA_{em}: Surface area of the pond when filled to the emergency spillway (ha)	.pnd
PND_PSA	SA_{pr}: Surface area of the pond when filled to the principal spillway (ha)	.pnd
PND_EVOL	V_{em}: Volume of water held in the pond when filled to the emergency spillway (10^4 m^3 H$_2$O)	.pnd
PND_PVOL	V_{pr}: Volume of water held in the pond when filled to the principal spillway (10^4 m^3 H$_2$O)	.pnd
WET_MXSA	SA_{mx}: Surface area of the wetland when filled to the maximum water level (ha)	.pnd
WET_NSA	SA_{nor}: Surface area of the wetland when filled to the normal water level (ha)	.pnd
WET_MXVOL	V_{mx}: Volume of water held in the wetland when filled to the maximum water level (m^3 H$_2$O)	.pnd
WET_NVOL	V_{nor}: Volume of water held in the wetland when filled to the normal water level (m^3 H$_2$O)	.pnd
PND_FR	fr_{imp}: Fraction of the subbasin area draining into the pond	.pnd
WET_FR	fr_{imp}: Fraction of the subbasin area draining into the wetland	.pnd

Table 27-2, cont.: SWAT input variables that pertain to ponds and wetlands

Variable name	Definition	File Name
PND_K	K_{sat}: Effective saturated hydraulic conductivity of the pond bottom (mm/hr)	.pnd
WET_K	K_{sat}: Effective saturated hydraulic conductivity of the wetland bottom (mm/hr)	.pnd
IFLOD1	$mon_{fld,beg}$: Beginning month of the flood season	.pnd
IFLOD2	$mon_{fld,end}$: Ending month of the flood season	.pnd
NDTARG	ND_{targ}: Number of days required for the reservoir to reach target storage	.pnd

27.3 DEPRESSIONS/POTHOLES

In areas of low relief and/or young geologic development, the drainage network may be poorly developed. Watersheds in these areas may have many closed depressional areas, referred to as potholes. Runoff generated within these areas flows to the lowest portion of the pothole rather than contributing to flow in the main channel. Other systems that are hydrologically similar to potholes include playa lakes and fields that are artifically impounded for rice production. The algorithms reviewed in this section are used to model these types of systems.

To define an HRU as a pothole, the user must set IPOT (.hru) to the HRU number. To initiate water impoundment, a release/impound operation must be placed in the .mgt file. The water balance for a pothole is:

$$V = V_{stored} + V_{flowin} - V_{flowout} + V_{pcp} - V_{evap} - V_{seep} \qquad 27.3.1$$

where V is the volume of water in the impoundment at the end of the day (m^3 H$_2$O), V_{stored} is the volume of water stored in the water body at the beginning of the day (m^3 H$_2$O), V_{flowin} is the volume of water entering the water body during the day (m^3 H$_2$O), $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H$_2$O), V_{pcp} is the volume of precipitation falling on the water body during the day (m^3 H$_2$O), V_{evap} is the volume of water removed from the water body by evaporation during the day (m^3 H$_2$O), and V_{seep} is the volume of water lost from the water body by seepage (m^3 H$_2$O).

27.3.1 SURFACE AREA

The surface area of the pothole is needed to calculate the amount of precipitation falling on the water body as well as the amount of evaporation and

seepage. Surface area varies with change in the volume of water stored in the impoundment. For surface area calculations, the pothole is assumed to be cone-shaped. The surface area is updated daily using the equation:

$$SA = \frac{\pi}{10^4} \cdot \left(\frac{3 \cdot V}{\pi \cdot slp} \right)^{2/3} \qquad\qquad 27.3.2$$

where *SA* is the surface area of the water body (ha), *V* is the volume of water in the impoundment (m^3 H$_2$O), and *slp* is the slope of the HRU (m/m).

27.3.2 PRECIPITATION

The volume of precipitation falling on the pothole during a given day is calculated:

$$V_{pcp} = 10 \cdot R_{day} \cdot SA \qquad\qquad 27.3.3$$

where V_{pcp} is the volume of water added to the water body by precipitation during the day (m^3 H$_2$O), R_{day} is the amount of precipitation falling on a given day (mm H$_2$O), and *SA* is the surface area of the water body (ha).

27.3.3 INFLOW

Water entering the pothole on a given day may be contributed from any HRU in the subbasin. To route a portion of the flow from an HRU into a pothole, the variable IPOT (.hru) is set to the number of the HRU containing the pothole and POT_FR (.hru) is set to the fraction of the HRU area that drains into the pothole. This must be done for each HRU contributing flow to the pothole. Water routing from other HRUs is performed only during the period that water impoundment has been activated (release/impound operation in .mgt). Water may also be added to the pothole with an irrigation operation in the management file (.mgt). Chapter 21 reviews the irrigation operation.

The inflow to the pothole is calculated:

$$V_{flowin} = irr + \sum_{hru=1}^{n} \left[fr_{pot,hru} \cdot 10 \cdot \left(Q_{surf,hru} + Q_{gw,hru} + Q_{lat,hru} \right) \cdot area_{hru} \right] \quad 27.3.4$$

where V_{flowin} is the volume of water flowing into the pothole on a given day (m^3 H$_2$O), *irr* is the amount of water added through an irrigation operation on a given day (m^3 H$_2$O), *n* is the number of HRUs contributing water to the pothole, $fr_{pot,hru}$

is the fraction of the HRU area draining into the pothole, $Q_{surf,hru}$ is the surface runoff from the HRU on a given day (mm H_2O), $Q_{gw,hru}$ is the groundwater flow generated in the HRU on a given day (mm H_2O), $Q_{lat,hru}$ is the lateral flow generated in the HRU on a given day (mm H_2O), and *area$_{hru}$* is the HRU area (ha).

27.3.4 EVAPORATION

The volume of water lost to evaporation on a given day is calculated:

$$V_{evap} = 10 \cdot \left(1 - \frac{LAI}{LAI_{evap}} \right) \cdot E_o \cdot SA \qquad \text{if } LAI < LAI_{evap} \qquad 27.3.5$$

$$V_{evap} = 0 \qquad \text{if } LAI \geq LAI_{evap} \qquad 27.3.6$$

where V_{evap} is the volume of water removed from the water body by evaporation during the day (m^3 H_2O), *LAI* is the leaf area index of the plants growing in the pothole, *LAI$_{evap}$* is the leaf area index at which no evaporation occurs from the water surface, E_o is the potential evapotranspiration for a given day (mm H_2O), and *SA* is the surface area of the water body (ha).

27.3.5 SEEPAGE

The volume of water lost by seepage through the bottom of the pothole on a given day is calculated as a function of the water content of the soil profile beneath the pothole.

$$V_{seep} = 240 \cdot K_{sat} \cdot SA \qquad \text{if } SW < 0.5 \cdot FC \qquad 27.3.7$$

$$V_{seep} = 240 \cdot \left(1 - \frac{SW}{FC} \right) \cdot K_{sat} \cdot SA \qquad \text{if } 0.5 \cdot FC \leq SW < FC \qquad 27.3.8$$

$$V_{seep} = 0 \qquad \text{if } SW \geq FC \qquad 27.3.9$$

where V_{seep} is the volume of water lost from the water body by seepage (m^3 H_2O), K_{sat} is the effective saturated hydraulic conductivity of the 1st soil layer in the profile (mm/hr), *SA* is the surface area of the water body (ha), *SW* is the soil water content of the profile on a given day (mm H_2O), and *FC* is the field capacity soil water content (mm H_2O). Water lost from the pothole by seepage is added to the soil profile.

27.3.6   OUTFLOW

Water may be removed from the pothole in three different types of outflow. When the volume of water in the pothole exceeds the maximum storage, the excess water is assumed to overflow and enter the main channel in the subbasin. When the retaining wall or berm is removed (this is done with a release/impound operation in the management file), all water stored in the pothole enters the main channel. The third type of flow from the pothole is via drainage tiles installed in the pothole.

27.3.6.1 OVERFLOW

Pothole outflow caused by overflow is calculated:

$$V_{flowout} = V - V_{pot,mx} \qquad \text{if } V > V_{pot.mx} \qquad 27.3.10$$

where $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H_2O), V is the volume of water stored in the pothole (m^3 H_2O), and $V_{pot,mx}$ is the maximum amount of water that can be stored in the pothole (m^3 H_2O).

27.3.6.2 RELEASE OPERATION

When a release operation is scheduled, all water in the pothole becomes outflow:

$$V_{flowout} = V \qquad\qquad 27.3.11$$

where $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H_2O), and V is the volume of water stored in the pothole (m^3 H_2O).

27.3.6.3 TILE FLOW

When drainage tiles are installed in a pothole, the pothole will contribute water to the main channel through tile flow. The pothole outflow originating from tile drainage is:

$$V_{flowout} = q_{tile} \cdot 86400 \qquad \text{if } V > q_{tile} \cdot 86400 \qquad 27.3.12$$

$$V_{flowout} = V \qquad\qquad \text{if } V \le q_{tile} \cdot 86400 \qquad 27.3.13$$

where $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3 H$_2$O), q_{tile} is the average daily tile flow rate (m^3/s), and V is the volume of water stored in the pothole (m^3 H$_2$O).

Table 27-3: SWAT input variables that pertain to potholes.

Variable name	Definition	File Name
IPOT	Number of HRU that is impounding water (that contains the pothole)	.hru
Variables in release/impound operation line:		
MONTH/DAY or HUSC	Timing of release/impound operation.	.mgt
MGT_OP	Operation code. MGT_OP = 13 for release/impound operation	.mgt
IREL_IMP	Release/impound action code: 0: impound, 1: release	.mgt
SLOPE	*slp*: Slope of the HRU (m/m)	.hru
POT_FR	*fr$_{pot}$*: Fraction of the HRU area draining into the pothole	.hru
EVLAI	*LAI$_{evap}$*: Leaf area index at which no evaporation occurs from the water surface	.bsn
POT_VOLX	$V_{pot,mx}$: Maximum amount of water that can be stored in the pothole (m^3 H$_2$O)	.hru
POT_TILE	q_{tile}: Average daily tile flow rate (m^3/s)	.hru

27.4 NOMENCLATURE

Area Subbasin area (ha)
E_o Potential evapotranspiration for a given day (mm H$_2$O)
FC Water content of the soil at field capacity (mm H$_2$O)
K_{sat} Effective saturated hydraulic conductivity of the reservoir bottom (mm/hr)
LAI Leaf area index of the plants growing in the pothole
LAI_{evap} Leaf area index at which no evaporation occurs from the water surface
ND_{targ} Number of days required for the reservoir to reach target storage
Q_{gw} Groundwater flow generated in a subbasin on a given day (mm H$_2$O)
Q_{lat} Lateral flow generated in a subbasin on a given day (mm H$_2$O)
Q_{surf} Surface runoff from the subbasin on a given day (mm H$_2$O)
R_{day} Amount of precipitation falling on a given day (mm H$_2$O)
SA Surface area of the water body (ha)
SA_{em} Surface area of the reservoir or pond when filled to the emergency spillway (ha)
SA_{mx} Surface area of the wetland when filled to the maximum water level (ha)
SA_{nor} Surface area of the wetland when filled to the normal water level (ha)
SA_{pr} Surface area of the reservoir when filled to the principal spillway (ha)
SW Average soil water content (mm H$_2$O)
V Volume of water in the impoundment at the end of the day (m^3 H$_2$O)
V_{em} Volume of water held in the reservoir when filled to the emergency spillway (m^3 H$_2$O)
V_{evap} Volume of water removed from the water body by evaporation during the day (m^3 H$_2$O)
V_{flowin} Volume of water entering the water body during the day (m^3 H$_2$O)

$V_{flowout}$ Volume of water flowing out of the water body during the day (m^3 H$_2$O)

$V'_{flowout}$ Initial estimate of the volume of water flowing out of the water body during the day (m^3 H$_2$O)

V_{mx} Volume of water held in the wetland when filled to the maximum water level (m^3 H$_2$O)

V_{nor} Volume of water held in the wetland when filled to the normal water level (m^3 H$_2$O)

V_{pcp} Volume of precipitation falling on the water body during the day (m^3 H$_2$O)

$V_{pot,mx}$ Maximum amount of water that can be stored in the pothole (m^3 H$_2$O)

V_{pr} Volume of water held in the reservoir when filled to the principal spillway (m^3 H$_2$O)

V_{seep} Volume of water lost from the water body by seepage (m^3 H$_2$O)

V_{stored} Volume of water stored in the water body at the beginning of the day (m^3 H$_2$O)

V_{targ} Target reservoir volume for a given day (m^3 H$_2$O)

$area_{hru}$ HRU area (ha)

$expsa$ Exponent for impoundment surface area calculation

fr_{imp} Fraction of the subbasin area draining into the impoundment

fr_{pot} Fraction of the HRU area draining into the pothole

irr Amount of irrigation water added on a given day (m^3 H$_2$O)

mon Month of the year

$mon_{fld,beg}$ Beginning month of the flood season

$mon_{fld,end}$ Ending month of the flood season

q_{out} Outflow rate (m^3/s)

q_{rel} Average daily principal spillway release rate (m^3/s)

$q_{rel,mn}$ Minimum average daily outflow for the month (m^3/s)

$q_{rel,mx}$ Maximum average daily outflow for the month (m^3/s)

q_{tile} Average daily tile flow rate (m^3/s)

slp Slope of the HRU (m/m)

$starg$ Target reservoir volume specified for a given month (m^3 H$_2$O)

β_{sa} Coefficient for impoundment surface area equation

η Evaporation coefficient (0.6)

EQUATIONS: SEDIMENT IN WATER BODIES

SWAT incorporates a simple mass balance model to simulate the transport of sediment into and out of water bodies. SWAT defines four different types of water bodies: ponds, wetlands, reservoirs and potholes. Sediment processes modeled in ponds, wetlands, reservoirs, and potholes are identical.

When calculating sediment movement through a water body, SWAT assumes the system is completely mixed. In a completely mixed system, as sediment enters the water body it is instantaneously distributed throughout the volume.

28.1 MASS BALANCE

The mass balance equation for sediment in a water body is:

$$sed_{wb} = sed_{wb,i} + sed_{flowin} - sed_{stl} - sed_{flowout}$$ 28.1.1

where sed_{wb} is the amount of sediment in the water body at the end of the day (metric tons), $sed_{wb,i}$ is the amount of sediment in the water body at the beginning of the day (metric tons), sed_{flowin} is the amount of sediment added to the water body with inflow (metric tons), sed_{stl} is the amount of sediment removed from the water by settling (metric tons), $sed_{flowout}$ is the amount of sediment transported out of the water body with outflow (metric tons).

28.2 SETTLING

The amount of suspended solid settling that occurs in the water body on a given day is calculated as a function of concentration. The initial suspended solid concentration is:

$$conc_{sed,i} = \frac{\left(sed_{wb,i} + sed_{flowin}\right)}{\left(V_{stored} + V_{flowin}\right)}$$ 28.2.1

where $conc_{sed,i}$ is the initial concentration of suspended solids in the water (Mg/m^3), $sed_{wb,i}$ is the amount of sediment in the water body at the beginning of the day (metric tons), sed_{flowin} is the amount of sediment added to the water body with inflow (metric tons), V_{stored} is the volume of water stored in water body or channel at the beginning of the day (m^3 H_2O), and V_{flowin} is the volume of water entering water body on given day (m^3 H_2O).

Settling occurs only when the sediment concentration in the water body exceeds the equilibrium sediment concentration specified by the user, $conc_{sed,eq}$. The concentration of sediment in the water body at the end of the day is calculated:

$$conc_{sed,f} = \left(conc_{sed,i} - conc_{sed,eq}\right) \cdot \exp\left[-k_s \cdot t \cdot d_{50}\right] + conc_{sed,eq}$$

$$\text{if } conc_{sed,i} > conc_{sed,eq}$$ 28.2.2

$$conc_{sed,f} = conc_{sed,i} \qquad \text{if } conc_{sed,i} \le conc_{sed,eq}$$ 28.2.3

where $conc_{sed,f}$ is the final sediment concentration in the water body (Mg/m^3), $conc_{sed,i}$ is the initial concentration of suspended solids in the water body (Mg/m^3), $conc_{sed,eq}$ is the equilibrium concentration of suspended solids in the water body (Mg/m^3), k_s is the decay constant (1/day), t is the length of the time step (1 day), and d_{50} is the median particle size of the inflow sediment (μm). Assuming 99% of the 1 μm size particles settle out of solution within 25 days, k_s is equal to 0.184. The median particle size of the inflow sediment is calculated:

$$d_{50} = \exp\left(0.41 \cdot \frac{m_c}{100} + 2.71 \cdot \frac{m_{silt}}{100} + 5.7 \cdot \frac{m_s}{100}\right) \qquad 28.2.4$$

where d_{50} is the median particle size of the inflow sediment (μm), m_c is percent clay in the surface soil layer in the subbasin, m_{silt} is the percent silt in the surface soil layer in the subbasin, m_s is the percent sand in the surface soil layer in the subbasin.

The amount of sediment settling out of solution on a given day is then calculated:

$$sed_{stl} = \left(conc_{sed,i} - conc_{sed,f}\right) \cdot V \qquad 28.2.5$$

where sed_{stl} is the amount of sediment removed from the water by settling (metric tons), $conc_{sed,i}$ is the initial concentration of suspended solids in the water body (Mg/m^3), $conc_{sed,f}$ is the final sediment concentration in the water body (Mg/m^3), and V is the volume of water in the impoundment (m^3 H_2O).

Table 28-1: SWAT input variables that pertain to sediment settling.

Variable Name	Definition	Input File
RES_NSED	$conc_{sed,eq}$: Equilibrium sediment concentration in water body (mg/L)	.res
PND_NSED	$conc_{sed,eq}$: Equilibrium sediment concentration in water body (mg/L)	.pnd
WET_NSED	$conc_{sed,eq}$: Equilibrium sediment concentration in water body (mg/L)	.pnd
POT_NSED	$conc_{sed,eq}$: Equilibrium sediment concentration in water body (mg/L)	.hru
CLAY	m_c: Percent clay in the surface soil layer in the subbasin	.sol
SILT	m_{silt}: Percent silt in the surface soil layer in the subbasin	.sol
SAND	m_s: Percent sand in the surface soil layer in the subbasin	.sol

28.3 SEDIMENT OUTFLOW

The amount of sediment transported out of the water body on a given day is calculated as a function of the final concentration. The initial suspended solid concentration is:

$$sed_{flowout} = conc_{sed,f} \cdot V_{flowout} \qquad 28.3.1$$

where $sed_{flowout}$ is the amount of sediment transported out of the water body with outflow (metric tons), $conc_{sed,f}$ is the final sediment concentration in the water body (Mg/m^3), and $V_{flowout}$ is the volume of outflow from the impoundment (m^3 H$_2$O).

28.4 NOMENCLATURE

V Volume of water in the impoundment (m^3 H$_2$O)
V_{flowin} Volume of water entering water body on given day (m^3 H$_2$O)
$V_{flowout}$ Volume of outflow from the impoundment (m^3 H$_2$O)
V_{stored} Volume of water stored in water body or channel (m^3 H$_2$O)

$conc_{sed}$ Concentration of suspended solids in the water (Mg/m^3)
$conc_{sed,eq}$ Equilibrium concentration of suspended solids in the water body (Mg/m^3)
d_{50} Median particle size of the inflow sediment (µm)
k_s Decay constant (1/day)
t Length of the time step (1 day)
m_c Percent clay in the surface soil layer in the subbasin
m_s Percent sand in the surface soil layer in the subbasin
m_{silt} Percent silt in the surface soil layer in the subbasin
sed_{flowin} Amount of sediment added to the water body with inflow (metric tons)
$sed_{flowout}$ Amount of sediment transported out of the water body (metric tons)
sed_{stl} Amount of sediment removed from the water by settling (metric tons)
sed_{wb} Sediment in the water body (metric tons)

CHAPTER **29**

EQUATIONS:
NUTRIENTS IN WATER BODIES

SWAT incorporates a simple empirical model to predict the trophic status of water bodies. For studies that require detailed modeling of lake water quality, SWAT has been linked to distributed lake water quality models such as WASP.

SWAT defines four different types of water bodies: ponds, wetlands, reservoirs and depressional/impounded areas (potholes). Nutrient processes modeled in ponds, wetlands and reservoirs are identical. Nutrient processes are not yet modeled in potholes.

29.1 NUTRIENT TRANSFORMATIONS

When calculating nutrient transformations in a water body, SWAT assumes the system is completely mixed. In a completely mixed system, as nutrients enter the water body they are instantaneously distributed throughout the volume. The assumption of a completely mixed system ignores lake stratification and intensification of phytoplankton in the epilimnion.

The initial amount of nitrogen and phosphorus in the water body on the given day is calculated by summing the mass of nutrient entering the water body on that day with the mass of nutrient already present in the water body.

$$M_{initial} = M_{stored} + M_{flowin}$$
<div align="right">29.1.1</div>

where $M_{initial}$ is the initial mass of nutrient in the water body for the given day (kg), M_{stored} is the mass of nutrient in the water body at the end of the previous day (kg), and M_{flowin} is the mass of nutrient added to the water body on the given day (kg).

In a similar manner, the initial volume of water in the water body is calculated by summing the volume of water entering the water body on that day with the volume already present in the water body.

$$V_{initial} = V_{stored} + V_{flowin}$$
<div align="right">29.1.2</div>

where $V_{initial}$ is the initial volume of water in the water body for a given day (m^3 H_2O), V_{stored} is the volume of water in the water body at the end of the previous day (m^3 H_2O), and V_{flowin} is the volume of water entering the water body on the given day (m^3 H_2O).

The initial concentration of nutrients in the water body is calculated by dividing the initial mass of nutrient by the initial volume of water.

Nutrient transformations simulated in ponds, wetlands and reservoirs are limited to the removal of nutrients by settling. Transformations between nutrient pools (e.g. $NO_3 \Leftrightarrow NO_2 \Leftrightarrow NH_4$) are ignored.

Settling losses in the water body can be expressed as a flux of mass across the surface area of the sediment-water interface (Figure 29-1) (Chapra, 1997).
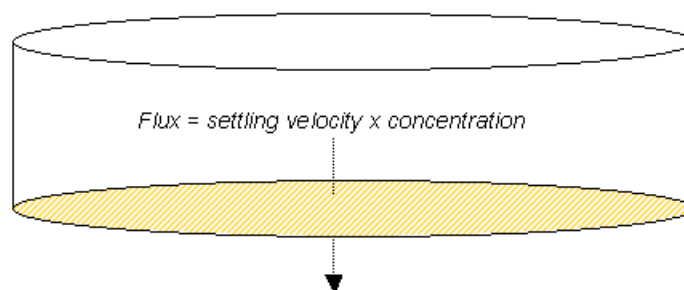

Figure 29-1: Settling losses calculated as flux of mass across the sediment-water interface.

The mass of nutrient lost via settling is calculated by multiplying the flux by the area of the sediment-water interface.

$$M_{settling} = v \cdot c \cdot A_s \cdot dt \qquad\qquad 29.1.3$$

where $M_{settling}$ is the mass of nutrient lost via settling on a day (kg), v is the apparent settling velocity (m/day), A_s is the area of the sediment-water interface (m^2), c is the initial concentration of nutrient in the water (kg/m^3 H$_2$O), and dt is the length of the time step (1 day). The settling velocity is labeled as "apparent" because it represents the net effect of the different processes that deliver nutrients to the water body's sediments. The water body is assumed to have a uniform depth of water and the area of the sediment-water interface is equivalent to the surface area of the water body.

The apparent settling velocity is most commonly reported in units of m/year and this is how the values are input to the model. For natural lakes, measured phosphorus settling velocities most frequently fall in the range of 5 to 20 m/year although values less than 1 m/year to over 200 m/year have been reported (Chapra, 1997). Panuska and Robertson (1999) noted that the range in apparent settling velocity values for man-made reservoirs tends to be significantly greater than for natural lakes. Higgins and Kim (1981) reported phosphorus

apparent settling velocity values from –90 to 269 m/year for 18 reservoirs in Tennessee with a median value of 42.2 m/year. For 27 Midwestern reservoirs, Walker and Kiihner (1978) reported phosphorus apparent settling velocities ranging from –1 to 125 m/year with an average value of 12.7 m/year. *A negative settling rate indicates that the reservoir sediments are a source of N or P; a positive settling rate indicates that the reservoir sediments are a sink for N or P*.

A number of inflow and impoundment properties affect the apparent settling velocity for a water body. Factors of particular importance include the form of phosphorus in the inflow (dissolved or particulate) and the settling velocity of the particulate fraction. Within the impoundment, the mean depth, potential for sediment resuspension and phosphorus release from the sediment will affect the apparent settling velocity (Panuska and Robertson, 1999). Water bodies with high internal phosphorus release tend to possess lower phosphorus retention and lower phosphorus apparent settling velocities than water bodies with low internal phosphorus release (Nürnberg, 1984). Table 29-1 summarizes typical ranges in phosphorus settling velocity for different systems.

Table 29-1: Recommended apparent settling velocity values for phosphorus (Panuska and Robertson, 1999)

Nutrient Dynamics	Range in settling velocity values (m/year)
Shallow water bodies with high net internal phosphorus flux	$v \leq 0$
Water bodies with moderate net internal phosphorus flux	$1 < v < 5$
Water bodies with minimal net internal phosphorus flux	$5 < v < 16$
Water bodies with high net internal phosphorus removal	$v > 16$

SWAT input variables that pertain to nutrient settling in ponds, wetlands and reservoirs are listed in Table 29-2. The model allows the user to define two settling rates for each nutrient and the time of the year during which each settling rate is used. A variation in settling rates is allowed so that impact of temperature and other seasonal factors may be accounted for in the modeling of nutrient settling. To use only one settling rate for the entire year, both variables for the nutrient may be set to the same value. Setting all variables to zero will cause the model to ignore settling of nutrients in the water body.

After nutrient losses in the water body are determined, the final concentration of nutrients in the water body is calculated by dividing the final mass of nutrient by the initial volume of water. The concentration of nutrients in outflow from the water body is equivalent to the final concentration of the nutrients in the water body for the day. The mass of nutrient in the outflow is calculated by multiplying the concentration of nutrient in the outflow by the volume of water leaving the water body on that day.

Table 29-2: SWAT input variables that control settling in ponds, wetlands and reservoirs.

Variable Name	Definition	Input File
IPND1	Beginning month of mid-year nutrient settling period for pond and wetland modeled in subbasin	.pnd
IPND2	Ending month of mid-year nutrient settling period for pond and wetland modeled in subbasin	.pnd
PSETL1	Phosphorus settling rate in pond during mid-year nutrient settling period ($IPND1 \leq month \leq IPND2$) (m/year)	.pnd
PSETL2	Phosphorus settling rate in pond during time outside mid-year nutrient settling period ($month < IPND1\ or\ month > IPND2$) (m/year)	.pnd
NSETL1	Nitrogen settling rate in pond during mid-year nutrient settling period ($IPND1 \leq month \leq IPND2$) (m/year)	.pnd
NSETL2	Nitrogen settling rate in pond during time outside mid-year nutrient settling period ($month < IPND1\ or\ month > IPND2$) (m/year)	.pnd
PSETLW1	Phosphorus settling rate in wetland during mid-year nutrient settling period ($IPND1 \leq month \leq IPND2$) (m/year)	.pnd
PSETLW2	Phosphorus settling rate in wetland during time outside mid-year nutrient settling period ($month < IPND1\ or\ month > IPND2$) (m/year)	.pnd
NSETLW1	Nitrogen settling rate in wetland during mid-year nutrient settling period ($IPND1 \leq month \leq IPND2$) (m/year)	.pnd
NSETLW2	Nitrogen settling rate in wetland during time outside mid-year nutrient settling period ($month < IPND1\ or\ month > IPND2$) (m/year)	.pnd
IRES1	Beginning month of mid-year nutrient settling period for reservoir	.lwq
IRES2	Ending month of mid-year nutrient settling period for reservoir	.lwq
PSETLR1	Phosphorus settling rate in reservoir during mid-year nutrient settling period ($IRES1 \leq month \leq IRES2$) (m/year)	.lwq
PSETLR2	Phosphorus settling rate in reservoir during time outside mid-year nutrient settling period ($month < IRES1\ or\ month > IRES2$) (m/year)	.lwq
NSETLR1	Nitrogen settling rate in reservoir during mid-year nutrient settling period ($IRES1 \leq month \leq IRES2$) (m/year)	.lwq
NSETLR2	Nitrogen settling rate in reservoir during time outside mid-year nutrient settling period ($month < IRES1\ or\ month > IRES2$) (m/year)	.lwq

29.2 TOTAL BALANCE

Assuming that the volume of the water body remains constant over time, the processes described above (inflow, settling, outflow) can be combined into the following mass balance equation for a well-mixed water body:

$$V \cdot \frac{dc}{dt} = W(t) - Q \cdot c - v \cdot c \cdot A_s \qquad 29.2.1$$

where V is the volume of the system (m^3 H$_2$O), c is the concentration of nutrient in the system (kg/m^3 H$_2$O), dt is the length of the time step (1 day), $W(t)$ is the amount of nutrient entering the water body during the day (kg/day), Q is the rate of water flow exiting the water body (m^3 H$_2$O/day), v is the apparent settling velocity (m/day), and A_s is the area of the sediment-water interface (m^2).

29.3 EUTROPHICATION

Under favorable conditions of light and temperature, excess amounts of nutrients in water can increase the growth of algae and other plants. The result of this growth is an increase in the rate of eutrophication, which is a natural ecological process of change from a nutrient-poor to a nutrient-rich environment. Eutrophication is defined as the process by which a body of water becomes enriched in dissolved nutrients (as phosphates) that stimulate the growth of aquatic plant life, usually resulting in the depletion of dissolved oxygen (Merriam-Webster, Inc., 1996).

Nutrient enrichment of moving waters and lakes is a normal result of soil weathering and erosion processes. The gradual evolution of Ice Age lakes into marshes and, eventually, organic soils is a result of eutrophication. However, this process can be accelerated by the discharge of wastes containing high levels of nutrients into lakes or rivers. One example of this is Lake Erie, which is estimated to have aged the equivalent of 150 natural years in a 15-year span of accelerated eutrophication.

Excessive plant growth caused by accelerated eutrophication can lead to stagnation of the water. The stagnation is caused by an increased biological

oxygen demand created by decaying plant remains. The result of this increased oxygen demand is a tendency toward anaerobic conditions and the inability of the water body to support fish and other aerobic organisms.

Nitrogen, carbon and phosphorus are essential to the growth of aquatic biota. Due to the difficulty of controlling the exchange of nitrogen and carbon between the atmosphere and water and fixation of atmospheric nitrogen by some blue-green algae, attempts to mitigate eutrophication have focused on phosphorus inputs. In fresh-water systems, phosphorus is often the limiting element. By controlling phosphorus loading, accelerated eutrophication of lake waters can be reduced.

In systems where phosphorus is the primary, controllable limiting nutrient of water body eutrophication, the amount of phosphorus present in the water body can be used to estimate the amount of eutrophication present in the water body.

29.3.1 PHOSPHORUS/CHLOROPHYLL *a* CORRELATIONS

A number of empirically derived equations have been developed to calculate chlorophyll *a* level as a function of total phosphorus concentration. SWAT uses an equation developed by Rast and Lee (1978) to calculate the chlorophyll *a* concentration in the water body.

$$Chla = 0.551 \cdot p^{0.76}$$
$$\text{29.3.1}$$

where *Chla* is the chlorophyll *a* concentration (μg/L) and *p* is the total phosphorus concentration (μg/L).

The equation has been modified to include a user-defined coefficient:

$$Chla = Chla_{co} \cdot 0.551 \cdot p^{0.76}$$
$$\text{29.3.2}$$

The user-defined coefficient, $Chla_{co}$, is included to allow the user to adjust the predicted chlorophyll *a* concentration for limitations of nutrients other than phosphorus. When $Chla_{co}$ is set to 1.00, equation 29.3.2 is equivalent to equation 29.3.1. For most water bodies, the original equation will be adequate..

29.3.2 CHLOROPHYLL *a*/SECCHI-DISK DEPTH CORRELATION

The secchi-disk depth is another measure of the trophic status of a water body. The secchi-disk depth quantifies the clarity of the water, an attribute easily perceived by the general public. The secchi-disk depth can be calculated from chlorophyll levels using the equation (Chapra, 1997):

$$SD = 6.35 \cdot Chla^{-0.473} \qquad\qquad 29.3.3$$

where *SD* is the secchi-disk depth (m) and *Chla* is the chlorophyll *a* concentration (µg/L).

For incorporation into SWAT, equation 29.3.3 was modified to include a user-defined coefficient:

$$SD = SD_{co} \cdot 6.35 \cdot Chla^{-0.473} \qquad\qquad 29.3.4$$

The user-defined coefficient, SD_{co}, is included to allow the user to adjust the predicted secchi-disk depth for impacts of suspended sediment and other particulate matter on water clarity that are ignored by the original equation. When SD_{co} is set to 1.00, equation 29.3.4 is equivalent to equation 29.3.3. For most water bodies, the original equation will be adequate.

While evaluation of water quality by secchi-disk depth measurements is subjective, some general correlations between secchi-disk depth and public perception of water quality have been made. One such correlation made for Annebessacook Lake in Maine (EPA, 1980) is given in Table 29-3.

Table 29-3: Relationship between secchi-disk depth and public perception of water quality.

Secchi-disk depth (m)	Public perception of water quality
0.0 – 0.9	gross pollution; water body totally unsuitable for recreation
1.0 – 1.9	algae blooms still evident; quality unacceptable for most uses
2.0 – 2.9	some complaints of declining water quality; some impairment of water use
3.0 – 3.9	satisfactory quality; no impairment of water use
4.0 – 4.9	excellent water quality; a positive factor encouraging use of lake
5.0 +	exceptional quality

Table 29-4: SWAT input variables that impact eutrophication calculations in ponds, wetlands and reservoirs.

Variable Name	Definition	Input File
CHLA	$Chla_{co}$ variable for calculation of chlorophyll *a* concentration in a pond	.pnd
CHLAW	$Chla_{co}$ variable for calculation of chlorophyll *a* concentration in a wetland	.pnd
CHLAR	$Chla_{co}$ variable for calculation of chlorophyll *a* concentration in a reservoir	.lwq
SECCI	SD_{co} variable for calculation of secchi-disk depth in a pond	.pnd
SECCIW	SD_{co} variable for calculation of secchi-disk depth in a wetland	.pnd
SECCIR	SD_{co} variable for calculation of secchi-disk depth in a reservoir	.lwq

29.4 NOMENCLATURE

A_s Area of sediment-water interface (m^2)

Chla Chlorophyll *a* concentration (μg/L)

$Chla_{co}$ User-defined coefficient to adjust predicted chlorophyll *a* concentration

M_{flowin} Mass of nutrient entering water body on the given day (kg)

$M_{initial}$ Initial mass of nutrient in water body for the given day (kg)

$M_{settling}$ Mass of nutrient lost via settling on a given day (kg)

M_{stored} Mass of nutrient in water body at end of previous day (kg)

Q Volumetric flow rate for water exiting water body (m^3 H_2O/day)

SD Secchi-disk depth (m)

SD_{co} User-defined coefficient to adjust predicted secchi-disk depth

V Volume of water in water body (assumed constant) (m^3 H_2O)

V_{flowin} Volume of water entering water body on given day (m^3 H_2O)

$V_{initial}$ Initial volume of water in water body on given day (m^3 H_2O)

V_{stored} Volume of water in water body at end of previous day (m^3 H_2O)

$W(t)$ Rate of nutrient loading (kg/day)

c Concentration of nutrient in the water (kg/m^3 H_2O)

dt Length of time step (1 day)

p Total phosphorus concentration (μg P/L)

ν Apparent settling velocity (m/day)

29.5 REFERENCES

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CHAPTER **30**

EQUATIONS: PESTICIDES IN WATER BODIES

SWAT incorporates a simple mass balance developed by Chapra (1997) to model the transformation and transport of pesticides in water bodies. The model assumes a well-mixed layer of water overlying a sediment layer. Figure 30-1 illustrates the mechanisms affecting the pesticide mass balance in water bodies.

SWAT defines four different types of water bodies: ponds, wetlands, reservoirs and depressional/impounded areas (potholes). Pesticide processes are modeled only in reservoirs.
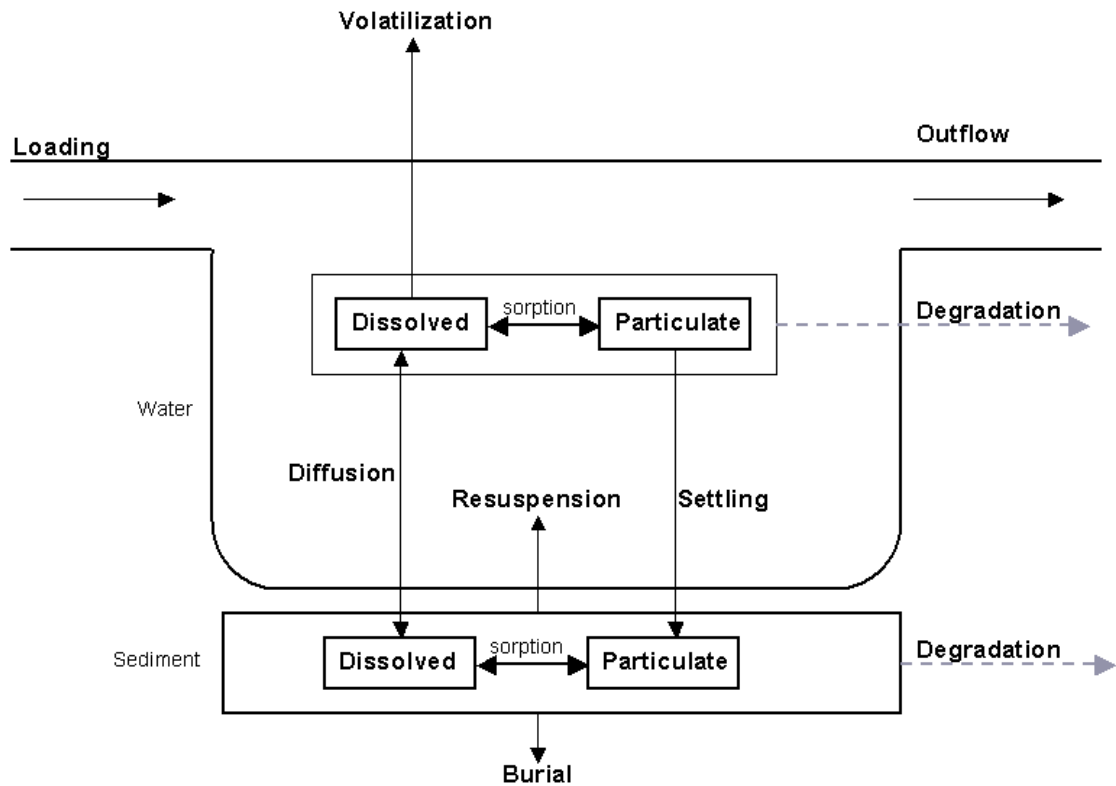
Figure 30-1: Pesticide mass balance for well-mixed water body with sediment layer.

30.1 PESTICIDE IN THE WATER

Pesticide in a well-mixed water body is increased through addition of mass in inflow, resuspension and diffusion from the sediment layer. The amount of pesticide in a well-mixed water body is reduced through removal in outflow, degradation, volatilization, settling and diffusion into the underlying sediment.

30.1.1 SOLID-LIQUID PARTITIONING

Pesticides will partition into particulate and dissolved forms. The fraction of pesticide in each phase is a function of the pesticide's partition coefficient and the water body's suspended solid concentration:

$$F_d = \frac{1}{1 + K_d \cdot conc_{sed}}$$
30.1.1

$$F_p = \frac{K_d \cdot conc_{sed}}{1 + K_d \cdot conc_{sed}} = 1 - F_d$$
30.1.2

where F_d is the fraction of total pesticide in the dissolved phase, F_p is the fraction of total pesticide in the particulate phase, K_d is the pesticide partition coefficient (m^3/g), and $conc_{sed}$ is the concentration of suspended solids in the water (g/m^3).

The pesticide partition coefficient can be estimated from the octanol-water partition coefficient (Chapra, 1997):

$$K_d = 3.085 \times 10^{-8} \cdot K_{ow} \tag{30.1.3}$$

where K_d is the pesticide partition coefficient (m^3/g) and K_{ow} is the pesticide's octanol-water partition coefficient ($\text{mg m}_{octanol}^{-3} \left(\text{mg m}_{water}^{-3}\right)^{-1}$). Values for the octanol-water partition coefficient have been published for many chemicals. If a published value cannot be found, it can be estimated from solubility (Chapra, 1997):

$$\log(K_{ow}) = 5.00 - 0.670 \cdot \log(pst'_{sol}) \tag{30.1.4}$$

where pst'_{sol} is the pesticide solubility (μmoles/L). The solubility in these units is calculated:

$$pst'_{sol} = \frac{pst_{sol}}{MW} \cdot 10^3 \tag{30.1.5}$$

where pst'_{sol} is the pesticide solubility (μmoles/L), pst_{sol} is the pesticide solubility (mg/L) and MW is the molecular weight (g/mole).

30.1.2 DEGRADATION

Pesticides in both the particulate and dissolved forms are subject to degradation. The amount of pesticide that is removed from the water via degradation is:

$$pst_{deg,wtr} = k_{p,aq} \cdot pst_{lkwtr} \tag{30.1.6}$$

where $pst_{deg,wtr}$ is the amount of pesticide removed from the water via degradation (mg pst), $k_{p,aq}$ is the rate constant for degradation or removal of pesticide in the water (1/day), and pst_{lkwtr} is the amount of pesticide in the water at the beginning of the day (mg pst). The rate constant is related to the aqueous half-life:

$$k_{p,aq} = \frac{0.693}{t_{1/2,aq}} \tag{30.1.7}$$

where $k_{p,aq}$ is the rate constant for degradation or removal of pesticide in the water (1/day), and $t_{1/2,aq}$ is the aqueous half-life for the pesticide (days).

30.1.3 VOLATILIZATION

Pesticide in the dissolved phase is available for volatilization. The amount of pesticide removed from the water via volatilization is:

$$pst_{vol,wtr} = v_v \cdot SA \cdot \frac{F_d \cdot pst_{lkwtr}}{V} \qquad 30.1.8$$

where $pst_{vol,wtr}$ is the amount of pesticide removed via volatilization (mg pst), v_v is the volatilization mass-transfer coefficient (m/day), SA is the surface area of the water body (m^2), F_d is the fraction of total pesticide in the dissolved phase, pst_{lkwtr} is the amount of pesticide in the water (mg pst), and V is the volume of water in the water body (m^3 H$_2$O).

The volatilization mass-transfer coefficient can be calculated based on Whitman's two-film or two-resistance theory (Whitman, 1923; Lewis and Whitman, 1924 as described in Chapra, 1997). While the main body of the gas and liquid phases are assumed to be well-mixed and homogenous, the two-film theory assumes that a substance moving between the two phases encounters maximum resistance in two laminar boundary layers where transfer is a function of molecular diffusion. In this type of system the transfer coefficient or velocity is:

$$v_v = K_l \cdot \frac{H_e}{H_e + R \cdot T_K \cdot (K_l / K_g)} \qquad 30.1.9$$

where v_v is the volatilization mass-transfer coefficient (m/day), K_l is the mass-transfer velocity in the liquid laminar layer (m/day), K_g is the mass-transfer velocity in the gaseous laminar layer (m/day), H_e is Henry's constant (atm m^3 mole^{-1}), R is the universal gas constant (8.206×10^{-5} atm m^3 (K mole)$^{-1}$), and T_K is the temperature (K).

For lakes, the transfer coefficients are estimated using a stagnant film approach:

$$K_l = \frac{D_l}{z_l} \qquad\qquad K_g = \frac{D_g}{z_g} \qquad 30.1.10$$

where K_l is the mass-transfer velocity in the liquid laminar layer (m/day), K_g is the mass-transfer velocity in the gaseous laminar layer (m/day), D_l is the liquid molecular diffusion coefficient (m²/day), D_g is the gas molecular diffusion coefficient (m²/day), z_l is the thickness of the liquid film (m), and z_g is the thickness of the gas film (m).

Alternatively, the transfer coefficients can be estimated with the equations:

$$K_l = K_{l,O_2} \cdot \left(\frac{32}{MW} \right)^{0.25}$$ (30.1.11)

$$K_g = 168 \cdot \mu_w \cdot \left(\frac{18}{MW} \right)^{0.25}$$ (30.1.12)

where K_l is the mass-transfer velocity in the liquid laminar layer (m/day), K_g is the mass-transfer velocity in the gaseous laminar layer (m/day), K_{l,O_2} is the oxygen transfer coefficient (m/day), MW is the molecular weight of the compound, and μ_w is the wind speed (m/s). Chapra (1997) lists several different equations that can be used to calculate K_{l,O_2}.

30.1.4 SETTLING

Pesticide in the particulate phase may be removed from the water layer by settling. Settling transfers pesticide from the water to the sediment layer. The amount of pesticide that is removed from the water via settling is:

$$pst_{stl,wtr} = v_s \cdot SA \cdot \frac{F_p \cdot pst_{lkwtr}}{V}$$ (30.1.13)

where $pst_{stl,wtr}$ is the amount of pesticide removed from the water due to settling (mg pst), v_s is the settling velocity (m/day), SA is the surface area of the water body (m²), F_p is the fraction of total pesticide in the particulate phase, pst_{lkwtr} is the amount of pesticide in the water (mg pst), and V is the volume of water in the water body (m³ H₂O).

30.1.5 OUTFLOW

Pesticide is removed from the water body in outflow. The amount of dissolved and particulate pesticide removed from the water body in outflow is:

$$pst_{sol,o} = Q \cdot \frac{F_d \cdot pst_{lkwtr}}{V}$$ 30.1.14

$$pst_{sorb,o} = Q \cdot \frac{F_p \cdot pst_{lkwtr}}{V}$$ 30.1.15

where $pst_{sol,o}$ is the amount of dissolved pesticide removed via outflow (mg pst), $pst_{sorb,o}$ is the amount of particulate pesticide removed via outflow (mg pst), Q is the rate of outflow from the water body (m^3 H$_2$O/day), F_d is the fraction of total pesticide in the dissolved phase, F_p is the fraction of total pesticide in the particulate phase, pst_{lkwtr} is the amount of pesticide in the water (mg pst), and V is the volume of water in the water body (m^3 H$_2$O).

Table 30-1: SWAT input variables that pesticide partitioning.

Variable Name	Definition	Input File
LKPST_KOC	K_d: Pesticide partition coefficient (m^3/g)	.lwq
LKPST_REA	$k_{p,aq}$: Rate constant for degradation or removal of pesticide in the water (1/day)	.lwq
LKPST_VOL	v_v: Volatilization mass-transfer coefficient (m/day)	.lwq
LKPST_STL	v_s: Pesticide settling velocity (m/day)	.lwq

30.2 PESTICIDE IN THE SEDIMENT

Pesticide in the sediment layer underlying a water body is increased through addition of mass by settling and diffusion from the water. The amount of pesticide in the sediment layer is reduced through removal by degradation, resuspension, diffusion into the overlying water, and burial.

30.2.1 SOLID-LIQUID PARTITIONING

As in the water layer, pesticides in the sediment layer will partition into particulate and dissolved forms. Calculation of the solid-liquid partitioning in the sediment layer requires a suspended solid concentration. The "concentration" of solid particles in the sediment layer is defined as:

$$conc_{sed}^* = \frac{M_{sed}}{V_{tot}}$$ 30.2.1

where $conc_{sed}^{*}$ is the "concentration" of solid particles in the sediment layer (g/m^3), M_{sed} is the mass of solid particles in the sediment layer (g) and V_{tot} is the total volume of the sediment layer (m^3).

Mass and volume are also used to define the porosity and density of the sediment layer. In the sediment layer, porosity is the fraction of the total volume in the liquid phase:

$$\phi = \frac{V_{wtr}}{V_{tot}} \qquad \text{30.2.2}$$

where ϕ is the porosity, V_{wtr} is the volume of water in the sediment layer (m^3) and V_{tot} is the total volume of the sediment layer (m^3). The fraction of the volume in the solid phase can then be defined as:

$$1 - \phi = \frac{V_{sed}}{V_{tot}} \qquad \text{30.2.3}$$

where ϕ is the porosity, V_{sed} is the volume of solids in the sediment layer (m^3) and V_{tot} is the total volume of the sediment layer (m^3).

The density of sediment particles is defined as:

$$\rho_s = \frac{M_{sed}}{V_{sed}} \qquad \text{30.2.4}$$

where ρ_s is the particle density (g/m^3), M_{sed} is the mass of solid particles in the sediment layer (g), and V_{sed} is the volume of solids in the sediment layer (m^3).

Solving equation 30.2.3 for V_{tot} and equation 30.2.4 for M_{sed} and substituting into equation 30.2.1 yields:

$$conc_{sed}^{*} = (1 - \phi) \cdot \rho_s \qquad \text{30.2.5}$$

where $conc_{sed}^{*}$ is the "concentration" of solid particles in the sediment layer (g/m^3), ϕ is the porosity, and ρ_s is the particle density (g/m^3).

Typical values of porosity and particle density for fine-grained sediments are $\phi = 0.8\text{-}0.95$ and $\rho_s = 2.4\text{-}2.7 \times 10^6$ g/m^3 (Chapra, 1997). Assuming $\phi = 0.8$ and $\rho_s = 2.6 \times 10^6$ g/m^3, the "concentration" of solid particles in the sediment layer is 5.2×10^5 g/m^3.

The fraction of pesticide in each phase is then calculated:

$$F_{d,sed} = \frac{1}{\phi + (1-\phi) \cdot \rho_s \cdot K_d}$$ 30.2.6

$$F_{p,sed} = 1 - F_{d,sed}$$ 30.2.7

where $F_{d,sed}$ is the fraction of total sediment pesticide in the dissolved phase, $F_{p,sed}$ is the fraction of total sediment pesticide in the particulate phase, ϕ is the porosity, ρ_s is the particle density (g/m³), and K_d is the pesticide partition coefficient (m³/g). The pesticide partition coefficient used for the water layer is also used for the sediment layer.

30.2.2 DEGRADATION

Pesticides in both the particulate and dissolved forms are subject to degradation. The amount of pesticide that is removed from the sediment via degradation is:

$$pst_{deg,sed} = k_{p,sed} \cdot pst_{lksed}$$ 30.2.8

where $pst_{deg,sed}$ is the amount of pesticide removed from the sediment via degradation (mg pst), $k_{p,sed}$ is the rate constant for degradation or removal of pesticide in the sediment (1/day), and pst_{lksed} is the amount of pesticide in the sediment (mg pst). The rate constant is related to the sediment half-life:

$$k_{p,sed} = \frac{0.693}{t_{1/2,sed}}$$ 30.2.9

where $k_{p,sed}$ is the rate constant for degradation or removal of pesticide in the sediment (1/day), and $t_{1/2,sed}$ is the sediment half-life for the pesticide (days).

30.2.3 RESUSPENSION

Pesticide in the sediment layer is available for resuspension. The amount of pesticide that is removed from the sediment via resuspension is:

$$pst_{rsp,wtr} = v_r \cdot SA \cdot \frac{pst_{lksed}}{V_{tot}}$$ 30.2.10

where $pst_{rsp,wtr}$ is the amount of pesticide removed via resuspension (mg pst), v_r is the resuspension velocity (m/day), SA is the surface area of the water body (m²),

pst_{lksed} is the amount of pesticide in the sediment (mg pst), and V_{tot} is the volume of the sediment layer (m^3). The volume of the sediment layer is calculated:

$$V_{tot} = SA \cdot D_{sed}$$
$\qquad$ 30.2.11

where V_{tot} is the volume of the sediment layer (m^3), SA is the surface area of the water body (m^2), D_{sed} is the depth of the active sediment layer (m). Pesticide removed from the sediment layer by resuspension is added to the water layer.

30.2.4 DIFFUSION

Pesticide in the dissolved phase is available for diffusion. Diffusion transfers pesticide between the water and sediment layers. The direction of movement is controlled by the pesticide concentration. Pesticide will move from areas of high concentration to areas of low concentration. The amount of pesticide that is transferred between the water and sediment by diffusion is:

$$pst_{dif} = \left| v_d \cdot SA \cdot \left(\frac{F_{d,sed} \cdot pst_{lksed}}{V_{tot}} - \frac{F_d \cdot pst_{lkwtr}}{V} \right) \right|$$
$\qquad$ 30.2.12

where pst_{dif} is the amount of pesticide transferred between the water and sediment by diffusion (mg pst), v_d is the rate of diffusion or mixing velocity (m/day), SA is the surface area of the water body (m^2), $F_{d,sed}$ is the fraction of total sediment pesticide in the dissolved phase, pst_{lksed} is the amount of pesticide in the sediment (mg pst), V_{tot} is the volume of the sediment layer (m^3), F_d is the fraction of total water layer pesticide in the dissolved phase, pst_{lkwtr} is the amount of pesticide in the water (mg pst), and V is the volume of water in the water body (m^3 H$_2$O). If $\dfrac{F_{d,sed} \cdot pst_{lksed}}{V_{tot}} > \dfrac{F_d \cdot pst_{lkwtr}}{V}$, pst_{dif} is transferred from the sediment to the water layer. If $\dfrac{F_{d,sed} \cdot pst_{lksed}}{V_{tot}} < \dfrac{F_d \cdot pst_{lkwtr}}{V}$, pst_{dif} is transferred from the water to the sediment layer.

The diffusive mixing velocity, v_d, can be estimated from the empirically derived formula (Chapra, 1997):

$$v_d = \frac{69.35}{365} \cdot \phi \cdot MW^{-2/3}$$
$\qquad$ 30.2.13

where v_d is the rate of diffusion or mixing velocity (m/day), ϕ is the sediment porosity, and MW is the molecular weight of the pesticide compound.

30.2.5 BURIAL

Pesticide in the sediment layer may be lost by burial. The amount of pesticide that is removed from the sediment via burial is:

$$pst_{bur} = v_b \cdot SA \cdot \frac{pst_{lksed}}{V_{tot}}$$
30.2.14

where pst_{bur} is the amount of pesticide removed via burial (mg pst), v_b is the burial velocity (m/day), SA is the surface area of the water body (m^2), pst_{lksed} is the amount of pesticide in the sediment (mg pst), and V_{tot} is the volume of the sediment layer (m^3).

Table 30-2: SWAT input variables related to pesticide in the sediment.

Variable Name	Definition	Input File
LKPST_KOC	K_d: Pesticide partition coefficient (m^3/g)	.lwq
LKSPST_REA	$k_{p,sed}$: Rate constant for degradation or removal of pesticide in the sediment (1/day)	.lwq
LKPST_RSP	v_r: Resuspension velocity (m/day)	.lwq
LKSPST_ACT	D_{sed}: Depth of the active sediment layer (m)	.lwq
LKPST_MIX	v_d: Rate of diffusion or mixing velocity (m/day)	.lwq
LKSPST_BRY	v_b: Pesticide burial velocity (m/day)	.lwq

30.3 MASS BALANCE

The processes described above can be combined into mass balance equations for the well-mixed water body and the well-mixed sediment layer:

$$\Delta pst_{lkwtr} = pst_{in} - \left(pst_{sol,o} + pst_{sorb,o}\right) - pst_{deg,wtr} - pst_{vol,wtr}$$

$$- pst_{stl,wtr} + pst_{rsp,wtr} \pm pst_{dif}$$ 30.3.1

$$\Delta pst_{lksed} = pst_{deg,sed} + pst_{stl,wtr} - pst_{rsp,wtr} - pst_{bur} \pm pst_{dif}$$ 30.3.2

where Δpst_{lkwtr} is the change in pesticide mass in the water layer (mg pst), Δpst_{lksed} is the change in pesticide mass in the sediment layer (mg pst), pst_{in} is the pesticide added to the water body via inflow (mg pst), $pst_{sol,o}$ is the amount of dissolved pesticide removed via outflow (mg pst), $pst_{sorb,o}$ is the amount of particulate pesticide removed via outflow (mg pst), $pst_{deg,wtr}$ is the amount of

pesticide removed from the water via degradation (mg pst), $pst_{vol,wtr}$ is the amount of pesticide removed via volatilization (mg pst), $pst_{stl,wtr}$ is the amount of pesticide removed from the water due to settling (mg pst), $pst_{rsp,wtr}$ is the amount of pesticide removed via resuspension (mg pst), pst_{dif} is the amount of pesticide transferred between the water and sediment by diffusion (mg pst), $pst_{deg,sed}$ is the amount of pesticide removed from the sediment via degradation (mg pst), pst_{bur} is the amount of pesticide removed via burial (mg pst)

30.4 NOMENCLATURE

D_g Gas molecular diffusion coefficient (m^2/day)
D_l Liquid molecular diffusion coefficient (m^2/day)
D_{sed} Depth of the active sediment layer (m)
F_d Fraction of total pesticide in the dissolved phase
$F_{d,sed}$ Fraction of total sediment pesticide in the dissolved phase
F_p Fraction of total pesticide in the particulate phase
$F_{p,sed}$ Fraction of total sediment pesticide in the particulate phase
H_e Henry's constant (atm m^3 mole^{-1})
K_d Pesticide partition coefficient (m^3/g)
K_g Mass-transfer velocity in the gaseous laminar layer (m/day)
K_l Mass-transfer velocity in the liquid laminar layer (m/day)
K_{l,O_2} Oxygen transfer coefficient (m/day)
M_{sed} Mass of solid phase in the sediment layer (g)
MW Molecular weight of the pesticide compound
Q Rate of outflow from the water body (m^3 H$_2$O/day)
R Universal gas constant (8.206 × 10^{-5} atm m^3 (K mole)$^{-1}$)
SA Surface area of the water body (m^2)
V Volume of water in the water body (m^3 H$_2$O)
V_{sed} Volume of solids in the sediment layer (m^3)
V_{tot} Total volume of the sediment layer (m^3)
V_{wtr} Volume of water in the sediment layer (m^3)

$conc_{sed}$ Concentration of suspended solids in the water (g/m^3)
$conc_{sed}^*$ "Concentration" of solid particles in the sediment layer (g/m^3)
$k_{p,aq}$ Rate constant for degradation or removal of pesticide in the water (1/day)
$k_{p,sed}$ Rate constant for degradation or removal of pesticide in the sediment (1/day)
pst_{bur} Amount of pesticide removed via burial (mg pst)
$pst_{deg,sed}$ Amount of pesticide removed from the sediment via degradation (mg pst)
$pst_{deg,wtr}$ Amount of pesticide removed from the water via degradation (mg pst)
pst_{dif} Amount of pesticide transferred between the water and sediment by diffusion (mg pst)

pst_{in} Pesticide added to the water body via inflow (mg pst)

pst_{lksed} Amount of pesticide in the sediment (mg pst)

pst_{lkwtr} Amount of pesticide in the water (mg pst)

$pst_{rsp,wtr}$ Amount of pesticide removed from sediment via resuspension (mg pst)

$pst_{sol,o}$ Amount of dissolved pesticide removed via outflow (mg pst)

$pst_{sorb,o}$ Amount of particulate pesticide removed via outflow (mg pst)

$pst_{stl,wtr}$ Amount of pesticide removed from the water due to settling (mg pst)

$pst_{vol,wtr}$ Amount of pesticide removed via volatilization (mg pst)

$t_{1/2,aq}$ Aqueous half-life for the pesticide (days)

$t_{1/2,sed}$ Sediment half-life for the pesticide (days)

v_b Pesticide burial velocity (m/day)

v_d Rate of diffusion or mixing velocity (m/day)

v_r Resuspension velocity (m/day)

v_s Settling velocity (m/day)

v_v Volatilization mass-transfer coefficient (m/day)

z_g Thickness of the gas film (m)

z_l Thickness of the liquid film (m)

ϕ Porosity

Δpst_{lkwtr} Change in pesticide mass in the water layer (mg pst)

Δpst_{lksed} Change in pesticide mass in the sediment layer (mg pst)

ρ_s Particle density (g/m^3)

μ_w Wind speed (m/s)

30.5 REFERENCES

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